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Assessment of Scotian Shelf Snow Crab in 2014

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Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

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TABLE OF CONTENTS

ABSTRACT iv
RÉSUMÉ v
MANAGEMENT 1
HISTORY 2
METHODS 2
- FISHERIES DATA 3
- RESEARCH SURVEY DATA 3
- PREDATION 6
- STOCK ASSESSMENT MODEL 6
- ECOSYSTEM INDICATORS 6

LIFE HISTORY 7
ECOSYSTEM CONTEXT 8
- OVERVIEW 8
- CONNECTIVITY 9
- ENVIRONMENTAL CONTROL (HABITAT) 12
- TOP-DOWN CONTROL (PREDATION) 12
- BOTTOM-UP CONTROL (RESOURCE LIMITATION) 14
- LATERAL CONTROL (COMPETITION) 14
- DISEASE 15
- HUMAN INFLUENCE 16
- FISHERY 18

RESOURCE STATUS 22
- SIZE STRUCTURE 22
- SEX RATIOS 22
- FEMALE NUMERICAL ABUNDANCE 23
- FISHABLE BIOMASS 24
- RECRUITMENT 24
- STOCK ASSESSMENT MODEL 24
- FISHING MORTALITY 25
- NATURAL MORTALITY 25

THE PRECAUTIONARY APPROACH 25
- REFERENCE POINTS AND HARVEST CONTROL RULES 26

RECOMMENDATIONS 27
- GENERAL REMARKS 27
- SOUTH-EASTERN NOVA SCOTIA (S-ENS) 28
- NORTH-EASTERN NOVA SCOTIA (N-ENS) 28
- AREA 4X 28

ACKNOWLEDGMENTS 29
REFERENCES 29
TABLES 35
FIGURES 44
GLOSSARY 107
APPENDICES 110
- APPENDIX 1: STOCK ASSESSMENT MODEL 110
- APPENDIX 2: CONTEXT OF THE PRECAUTIONARY APPROACH 114
- APPENDIX 3: ECOSYSTEM INDICATORS 118

ABSTRACT

Snow crab landings in 2014 for North-Eastern Nova Scotia (N-ENS) and South-Eastern Nova Scotia (S-ENS) were 778 t and 11,267 t, respectively, and they were 79 t in Crab Fishing Area (CFA) 4X for the 2013/2014 season, representing a decrease of 1% (N-ENS) and decreases of 1% (S-ENS) and 33% (4X) relative to the previous year. Total allowable catches (TACs) in 2014 were 783 t, 11,311 t and 80 t in N-ENS, S-ENS and 4X. Non-standardized catch rates in 2014 were 104 kg/trap haul in N-ENS, 112 kg/trap haul in S-ENS, and 15 kg/trap haul in 4X in 2013/2014 which, relative to the previous year, represents a decrease of 2%, an increase of 8% and an increase of 25%, respectively. The capture of soft-shelled crab in N-ENS stayed stable at 3% over the past two seasons. In S-ENS, the relative occurrence of soft-shell crab was 2% for each of the last two seasons. Soft-shell discard rates in 4X remain very low, due to it being a fall and winter fishery. Soft-shell incidence and associated potential handling mortality continues to be an issue requiring diligent and adaptive management action. Bycatch of non-target species is extremely low (<0.01%) in N-ENS and S-ENS. CFA 4X bycatch levels increased to 2%, likely associated with decreased catch rates and landings of snow crab. Although very limited local recruitment into the fishery is expected for the short to medium term in N-ENS, a pulse of unexpected CC1 and CC2 crab did appear during the fishery, likely through migration; however, this same pulse of crab was not observed during the autumn survey. There remains a gap in the length frequency of male crab in N-ENS between 60 mm and 95 mm carapace width. Male crab were observed in all size classes in S-ENS, suggesting more stable recruitment into the future. CFA 4X shows little potential for substantial internal recruitment to the fishery for the next four to five years. Movement will likely be an important source of 4X crab for the next several years. The low abundance of both the mature and immature crab in the adjacent portion of CFA 24 and erratic temperature fields in 4X create future uncertainties. The mature component of female snow crab in all areas appear to be low and decreasing, however, there does appear to be positive signs of immature female snow crab in both N-ENS and S-ENS. The post-fishery fishable biomass index of snow crab in N-ENS was estimated to be 2,075 t (3,451 t in 2013). In S-ENS, the post-fishery fishable biomass index was estimated to be 40.1×10^3 t (46.2×10^3 t in 2013). In 4X, the pre-fishery fishable biomass was 2,059 t (503 t in 2013/2014), however, the biomass estimate in this area is uncertain as only a subset of survey stations were completed. These population characteristics are tempered by a number of uncertainties, including the influence of predation, especially upon immature and soft-shelled snow crab by groundfish, as well as large and rapid temperature swings (especially in CFA 4X and parts of CFA 24), as they can have both direct and indirect influences upon snow crab, which are cold-water stenotherms. Signs of a potential return of ecological, social, and economic indicators in the direction of a system less dominated by invertebrates adds further uncertainty to the medium- to long-term sustainability of the population. Fishing mortality in N-ENS was estimated to be 0.30, and has increased slightly since 2009. Fishable biomass has been decreasing for the past several years, mainly through a lack of recruitment. The unexpected increase in proportion of CC1 and CC2 crab during the fishery may have helped to bolster the stock and catch rates during the season. In N-ENS, medium- to long-term prospects are uncertain and potentially poor due to an absence of pre-recruits. The fishable biomass is in the "healthy" zone. In N-ENS, a decrease in TAC is recommended. Fishing mortality in S-ENS was estimated to be 0.18, relatively unchanged since 2009. Good recruitment suggests a positive outlook. The fishable biomass is in the "healthy" zone. In S-ENS a status quo to a marginal decrease in harvest strategy is recommended. Fishing mortality in 4X for 2013/2014 was estimated to be 0.08, largely due to the large reduction in TAC. In 4X, the modeled fishable biomass moved from the "cautious" into the "healthy" zone, albeit with considerable uncertainty, and recruitment into next season is uncertain. A continued conservative harvest strategy is recommended pending further analysis prior to the 2015-2016 season.

Évaluation des stocks de crabes des neiges du plateau néo écossais en 2014

RÉSUMÉ

En 2014, les débarquements de crabe des neiges dans le nord-est et le sud-est de la Nouvelle-Écosse ont atteint respectivement 778 t et 11 267 t, et les débarquements dans la zone de pêche du crabe (ZPC) 4X ont atteint 79 t pour la saison 2013-2014, ce qui représente une diminution de 1 % (nord-est de la Nouvelle-Écosse), une diminution de 1 % (sud-est de la Nouvelle-Écosse) et une diminution de 33 % (ZPC 4X) par rapport à l'année précédente. Les totaux autorisés de captures (TAC) de 2014 étaient de 783 t, 11 311 t et 80 t dans le nord-est de la Nouvelle-Écosse, le sud-est de la Nouvelle-Écosse et la zone 4X. En 2014, les taux de prise non normalisés étaient de 104 kg/casier levé dans le nord-est de la Nouvelle-Écosse, de 112 kg/casier levé dans le sud-est de la Nouvelle-Écosse, et de 15 kg/casier levé dans la ZPC 4X en 2013-2014, ce qui représente une diminution de 2 %, une augmentation de 8 % et une augmentation de 25 %, respectivement, par rapport à l'année précédente. Le nombre de prises de crabes à carapace molle dans le nord-est de la Nouvelle-Écosse est demeuré stable à un taux de 3 % au cours des deux dernières saisons. Dans le sud-est de la Nouvelle-Écosse, la présence relative de crabes à carapace molle était de 2 % pour les deux dernières saisons. Les taux de rejet de crabes à carapace molle dans 4X demeurent très bas, étant donné que la pêche a lieu pendant l'automne et l'hiver. La présence des crabes à carapace molle et la mortalité potentielle connexe due à la manutention continuent d'être un enjeu nécessitant des mesures de diligence et de gestion adaptative. Les prises accessoires d'espèces non ciblées sont très faibles (moins de 0,01 %) dans le nord-est de la Nouvelle-Écosse et le sud-est de la Nouvelle-Écosse. Les niveaux de prises accessoires dans la ZPC 4X ont augmenté à 2 %, ce qui est probablement lié à une diminution des taux de capture et de débarquement de crabes des neiges. Même si l'on s'attend à ce que le recrutement local dans la pêche soit très limité à court et à moyen terme dans le nord-est de la Nouvelle-Écosse, on a observé un grand nombre inattendu de crabes des catégories CC1 et CC2 pendant la pêche, probablement grâce à la migration; toutefois, ce grand nombre de crabes n'a pas été observé dans le relevé effectué à l'automne. Il existe encore un écart dans la fréquence de longueur des crabes mâles dans le nord-est de la Nouvelle-Écosse dont la largeur de la carapace est de 60 à 95 mm. Des crabes mâles de toutes les catégories de taille ont été observés dans le sud-est de la Nouvelle-Écosse, laissant entrevoir un recrutement futur plus stable. Dans la ZPC 4X, le potentiel de recrutement interne important dans la pêche au cours des quatre à cinq prochaines années est faible. Les déplacements seront probablement une source importante de la présence de crabes dans la ZPC 4X au cours des prochaines années. La quantité limitée de crabes matures et immatures dans la partie voisine de la ZPC 24 et les champs de température irréguliers dans 4X créent des incertitudes pour l'avenir. Le nombre de crabes des neiges femelles adultes dans toutes les zones semble faible et décroissant; toutefois, la présence apparente de crabes des neiges femelles immatures est de bon augure dans le nord-est de la Nouvelle-Écosse et le sud-est de la Nouvelle-Écosse. Dans le nord-est de la Nouvelle-Écosse, l'indice de la biomasse exploitable de crabes des neiges après la saison de pêche a été estimé à 2 075 t (3 451 t en 2013). Dans le sud-est de la Nouvelle-Écosse, l'indice de la biomasse exploitable de crabes des neiges après la saison de pêche a été estimé à 40,1 × 103 t (46,2 × 103 t en 2013). Dans la ZPC 4X, la biomasse exploitable avant la pêche était de 2 059 t (503 t en 2013-2014); toutefois, l'estimation de la biomasse dans cette zone est incertaine, car seul un sous-ensemble de stations a fait l'objet de relevés. Ces caractéristiques des populations sont modérées par un certain nombre d'incertitudes, y compris l'influence de la prédation par les poissons de fond, plus particulièrement sur les crabes des neiges immatures et à carapace molle, et les fluctuations rapides et importantes de température (surtout dans la ZPC 4X et certaines parties de la ZPC 24), car celles-ci peuvent avoir des répercussions directes et indirectes sur les crabes des neiges, qui sont des sténothermes d'eau froide. Les signes d'un retour potentiel des indicateurs

écologiques, sociaux et économiques pointant vers l'émergence d'un système moins dominé par les invertébrés accroissent l'incertitude quant à la viabilité à moyen et à long terme de la population. La mortalité par pêche dans le nord-est de la Nouvelle-Écosse a été estimée à 0,30 et a augmenté légèrement depuis 2009. La biomasse exploitable a diminué au cours des dernières années, principalement en raison d'un manque de recrutement. L'augmentation inattendue de la proportion de crabes des catégories CC1 et CC2 au cours de la pêche pourrait avoir contribué à renforcer le stock et les taux de prise au cours de la saison. Dans le nord-est de la Nouvelle-Écosse, les perspectives à moyen et à long terme sont incertaines et pourraient être médiocres en raison de l'absence de prérecrues. La biomasse exploitable se situe dans la zone saine. Dans le nord-est de la Nouvelle-Écosse, on recommande une diminution dans les captures. La mortalité par pêche dans le sud-est de la Nouvelle-Écosse a été estimée à 0,18 (elle est demeurée relativement la même depuis 2009). Le bon recrutement est de bon augure. La biomasse exploitable se situe dans la zone saine. Dans le sud-est de la Nouvelle-Écosse, on recommande le statu quo ou une diminution très légère dans les captures. La mortalité par pêche dans la ZPC 4X pour la saison 2013-2014 a été estimée à 0,08, principalement en raison de la diminution importante du TAC. Dans la zone 4X, la biomasse exploitable modélisée est passée de la zone de « prudence » à la zone « saine », bien qu'une incertitude considérable règne et que le recrutement pour la prochaine saison est incertain. Il est recommandé d'adopter une stratégie de pêche prudente en attendant une analyse plus poussée avant la saison 2015-2016.

MANAGEMENT

The Scotian Shelf Ecosystem (SSE) snow crab fishery is managed as three main areas: North-Eastern Nova Scotia (N-ENS), South-Eastern Nova Scotia (S-ENS) and Crab Fishing Area (CFA) 4X (Table 1; Figure 1). These areas are *ad hoc* divisions based upon political, social, economic and historical convenience, with little biological basis.

Fishing seasons have also had a complex evolution based upon economic, safety and conservation considerations: severe weather conditions; catch of soft-shell and white crab; disruption of mating periods; and overlap with other fisheries, especially lobster and northern shrimp. From 1982 to 1993, the management of the ENS fisheries was based on effort controls (size, sex, shell-hardness, season, license, trap limits). Additional management measures were introduced from 1994 to 1999: Individual Boat Quotas (IBQs), Total Allowable Catches (TACs), 100% dockside monitoring, mandatory logbooks and at-sea monitoring by certified observers (currently at levels of 5%, 5%, and 10% in N-ENS, S-ENS, and 4X, respectively). Vessel Monitoring Systems (VMS) have been implemented in S-ENS and 4X, and voluntary management measures requested by fishers were also introduced in some areas, such as a shortened fishing season and reduced numbers of traps. The designation of a "temporary license" holder was dropped in 2005.

In 2006, the soft-shell protocol was modified in S-ENS due to the expectation of an increased incidence of soft-shelled snow crab and the potential harm associated with handling mortality. Soft-shelled crab incidence observed by at-sea-observers was relayed to Fisheries and Oceans Canada (DFO) within 24 hours of landing, plotted on a two-minute grid and re-broadcast to all members of industry on the ENS Snow Crab web location (as well as via email and fax).

Fishers are asked to voluntarily avoid fishing within 1.5 nautical miles of the locations that had greater than 20% soft crab in the observed catch. This adaptive fishing protocol allows rapid adjustment of fishing effort, shifting gear away from, or altogether avoiding, potentially problematic areas and also helping to save time, fuel and other costs. This approach was not required in 4X due to the low incidence of soft crab in the catch and not adopted in N-ENS due to the very short season. However, due to high soft-shell incidence in N-ENS in 2007/2008, direct management measures were implemented to address concerns of soft-shell handling mortality. These measures now include a spring season, in addition to the traditional summer season, and the potential closure of sub-areas based on observer reports of high soft crab incidence. Finally, the voluntary return to the sea of immature, legal sized crab (> 95 mm carapace width (CW); "pencil-clawed" crab) was implemented in 2006 for all areas on the SSE, to allow these crab to complete their molting cycle and molt to maturity, thereby, simultaneously increasing the total yield per crab captured, as well as the total lifetime reproductive success of these large-sized males.

In 1996, DFO (Gulf Fisheries Centre (GFC), Moncton, New Brunswick) and SSE snow crab fishers initiated a Joint Project Agreement to assess SSE snow crab using a fisheries-independent trawl survey (Biron et al. 1997). It was officially accepted for use as an assessment tool in 1999. These surveys demonstrated the presence of unexploited crab in the south-eastern areas of the SSE, which subsequently led to large increases in TACs (Tables 2-4), fishing effort, landings and catch rates (Figures 2-4) and the addition of new participants. Trawl surveys were formally extended to 4X in 2004. This Joint Project Agreement (now "Collaborative Agreement") has continued to the present.

HISTORY

The snow crab fishery is currently the second most valuable commercial fishery in Atlantic Canada and third in Nova Scotia. It has been active since the mid-1970s (Figure 2). The earliest records of landings were at levels of less than 1,000 t, mostly in the near-shore areas of ENS (Figure 3). By 1979, landings rose to 1,500 t, subsequent to which the fishery declined substantially in the mid-1980s and was considered a collapsed fishery. Recruitment to the fishery was observed in 1986 and, since that time, landings have increased considerably (Figure 3). In 1994, directed fishing for snow crab began in 4X, the southern-most range of distribution and continues at low harvest levels.

Annual TACs (Tables 2-4) increased to a peak in 2002/2003 at 9,113 t in S-ENS and 1,493 t in N-ENS. Approximately 10,000 t of snow crab were landed each year from 2000 to 2004. Thus, the post-1998 period was one of rapid expansion of both the economic importance of the crab fishery and also the spatial extent of the exploitation. In 2004, with persistent low levels of recruitment and a steady decline in fishable biomass estimates, since the early-2000s, precautionary exploitation strategies were adopted throughout the SSE. In S-ENS, TACs rose from 2005 to reach a previously unseen level in 2010. They have declined slightly in each of the following two seasons due to declines in fishable biomass estimates; however, TACs have been stable at 11,311 t in each of the past two years. In N-ENS, due to negligible recruitment, TACs were maintained at low levels until 2009, but have been slowly increasing since that time. Though 2013 and 2014 still showed limited potential for recruitment in N-ENS, target exploitation rates were increased to avoid excessive ageing and subsequent death of too large a portion of the fishable population. The 2012/2013 TAC for 4X was lowered due to decreases in biomass estimates and commercial catch rates (Figure 4). As a result of the poor 2012/2013 fishing season in 4X, the 4X TAC for 2013/2014 was drastically decreased, being well below the 10 year mean TAC for the area. The TAC of 80 t in 4X was used in 2014/2015 to maintain reduced exploitation rates as the stock entered the cautious zone.

A Marine Stewardship Council Certification was granted to the ENS fishery in September 2011. A surveillance audit was successfully completed in September 2014.

METHODS

The primary driver of the analytical approaches developed for the assessment of snow crab on the SSE is the high temporal and spatial variability in spatial distributions of snow crab. This is likely due to the area being the southern-most extreme of the species' distributional range in the northwest Atlantic. All data analyses were implemented in the statistical computing language and environment R (R Development Core Team 2012) to allow migration and documentation of methods into the future. The complete analytical suite, coded in R, is posted to a GitHub repository website.

A number of spatial and/or temporal interpolation methods are used in this assessment. Thin-plate-splines visualizations were computed with Generic Mapping Tools (Wessel and Smith 1998, version 4.1) with a tension parameter T = 0.4 and a spatial extent of interpolation of 16 km radius from every datum, a range comparable with that observed in the empirical variograms of many variables (Choi and Zisserson 2012). Conversions between cartographic and Cartesian co-ordinate systems for analytical purposes were computed with PROJ (Evenden 1995, version 4.4.9) onto the Universal Transverse Mercator grid system (UTM region 20).

FISHERIES DATA

Fishery catch rates are potentially biased indicators of crab abundance. The spatial and temporal distribution of both crabs and the fishing effort are not uniform, varying strongly with season, bottom temperatures, food availability, timing of spring plankton blooms, reproductive behavior, substrate/shelter availability, relative occurrence of soft and immature crab, species composition, fisher experience, bait type and soak time and ambient currents. Catch rates have not been adjusted for these influences and are presented here only to maintain continuity with historical records. Fishery catch rates are used as a measure of fishery performance and not stock performance.

Mandatory logbooks provide information on location, effort (number of trap hauls) and landings (verified by dockside monitoring). The data are stored in the MARFIS database (Maritimes Region, Policy and Economics Branch, Commercial Data Division). Data were quality checked.

At-sea-observed data provides information about the size structure and the carapace condition (CC) of the commercially exploited stock (Table 5; Figure 5). The data are stored in the Observer Database System. At-sea-observers are deployed randomly with the coverage being as evenly distributed as possible between vessels. The target coverage (as a percent of total landings observed) was 5% in S-ENS and N-ENS and 10% for 4X. This was a decrease from 10% in S-ENS and was agreed upon by DFO Science, Management and Conservation and Protection (Enforcement) in consultation with industry. This information was also used to compute the potential bycatch of other non-snow crab species by the snow crab fishery. Bycatch estimates of each species *i*, was extrapolated from the biomass of species *i*, observed in the catch and the relative observer coverage by:

$$\text{Bycatch}_i\ [\text{kg}] = \text{Observed catch}_i\ [\text{kg}] \times \text{Total snow crab landings [kg]} / \text{Observed catch}_{\text{snow crab}}\ [\text{kg}]$$

RESEARCH SURVEY DATA

Spatial coverage in the survey is (1) extensive, going well beyond all known commercial fishing grounds and (2) intensive, with a minimum of one survey station located pseudo-randomly in every 10 × 10 minute area (Figure 6). This sampling design was initially developed to facilitate geostatistical estimation techniques (Cressie 1993). Additional stations have been added adaptively, based upon attempts to reduce local estimates of prediction variance, as well as identifying the spatial bounds of snow crab habitat. Between 2004 and 2013, approximately 400 stations have been sampled annually on the fishing vessel, *The Gentle Lady*, with the same captain. Due to the sinking of *The Gentle Lady* in December 2013 during a commercial fishing trip, the 2014 survey was conducted with a new fishing vessel with similar characteristics, named the *Ms. Jessie*. To maintain a consistent time series the same captain, crew, net and net monitoring systems were used in 2014 as had been used since 2004. There was a delay in getting the survey underway due to unforeseen circumstances in 2014, which resulted in a reduction in the total number of survey stations being completed of 359 stations. The removal of stations was done at the start of the survey to avoid any potential biases or gaps in survey distribution for N-ENS and S-ENS (Figure 6). The western most component of the 4X survey stations were not completed, which will lead to higher uncertainty in results for this area.

The extensiveness of the sampling design allows the objective determination of the spatial bounds of the snow crab population; information that must be known if reliable estimates of biomass and population structure (e.g., size, sex, maturity) are to be made. The spatial distribution of snow crab is quite dynamic and so can rapidly shift to areas where they are not "traditionally" found. In addition, the distributional patterns of immature, soft-shelled, very old and female crabs do not correspond completely to those of legal size males. The former are considered to be less competitive and more susceptible to predation (Hooper 1986) and usually

observed in environments or substrates with greater cover (gravel, rocks; Comeau et al. 1998). Sampling that focused upon only those areas where large hard-shelled males occur in high frequency would preclude the reliable estimation of the relative abundance of these other important segments of the crab population.

Due to the gradual evolution of the aerial extent and alterations in the intensity and timing of surveys since the mid-1990s, direct inter-annual comparisons of the data are made difficult over the entire time series. Currently, surveys are conducted in the autumn (September to December; i.e., post-fishing season in ENS and just prior to the fishing season in 4X). The timing of the survey has stabilized to this latter period only since 2004. Prior to 2004, surveys were conducted during the spring/summer (April to July; i.e., prior to the fishing season in ENS). As a consequence, temporal trends are most reliable for the post-2004 period. In the southern-most area of snow crab distribution (4X), trawl survey coverage has been historically sporadic but has stabilized since 2004. In all areas, fishing grounds are left fallow for as long as possible from timing of commercial fishing to the surveying of that particular area. This allows for crab populations to redistribute as naturally as possible following localized removals (i.e., commercial catches). Late fishing efforts can impact this natural redistribution of crab.

A *Bigouden Nephrops* trawl, a net originally designed to dig into soft sediments for the capture of a lobster species in Europe, was used to sample the snow crab and other benthic fauna (headline of 20 m, 27.3 m foot rope mounted with a 3.2 m long, 8 mm chain, with a mesh size of 80 mm in the wings and 60 mm in the belly and 40 mm in the cod-end). Net configuration was recorded with wireless trawl monitoring sensors; depth and temperature were recorded with Seabird SBE 39 temperature and depth recorders; and positional information was recorded with a global positioning system. Actual duration of bottom contact was assessed from trawl monitoring and Seabird data streams. The ship speed was maintained at approximately two knots. The warp length was approximately three times the depth. Swept area of the net was computed from swept distance and monitored net width.

All crab were enumerated; measured with callipers; shell condition determined (Table 5); claw hardness measured with a durometer; and weighed with motion-compensated scales. The latter allowed direct biomass measurement rather than relying upon allometric relationships between body parts to approximate biomass (the latter was the approach prior to 2004; see below). Captured crabs were also visually examined for the occurrence of Bitter Crab Disease (BCD). Data entry and quality control was provided by Javitech Ltd. and migrated onto the Observer Database System, held at DFO, BIO (Bedford Institute of Oceanography, Dartmouth, Nova Scotia).

Snow crab biomass estimates prior to 2004 were approximated from CW measurements by applying an allometric relationship developed for SSE adult hard shelled snow crab (Biron et al. 1999; R^2=0.98, n=750):

$$mass\ [g] = 1.543 \times 10^{-4} \times CW\ [mm]^{3.206}$$

Weights of individual animals have been directly assessed by digital scale since 2004. This replaces weights approximated from CW whenever possible.

The maturity status of males was determined from a combination of biological staging through CC and morphometric analysis. While physiological maturity is not directly coincident with the onset of morphometric maturity (Sainte-Marie 1993), the latter is more readily determined.

In the terminal molt of male snow crab, a disproportionate increase of chela height (CH) relative to CW is generally observed. Morphometrically mature males ($M_{(male)}$) can be discriminated from morphometrically immature males via the following equation (E. Wade, personal communication, GFC):

$$M_{(male)} = -25.324 \cdot \ln(CW\ [mm]) + 19.776 \cdot \ln(CH\ [mm]) + 56.650$$

where an individual is considered mature if $M_{(male)} > 0$.

The maturity status of females is assessed from direct visual inspection of eggs or gonad development. Where maturity status was ambiguous, maturity was determined morphometrically, as the width of abdomen (measured by the width of the fifth abdominal segment, AW) increases rapidly relative to CW at the onset of morphometric maturity, facilitating the brooding of eggs. This onset of morphometric maturity ($M_{(female)}$) can be delineated via the following equation (E. Wade, personal communication, GFC):

$$M_{(female)} = -16.423 \cdot \ln(CW\ [mm]) + 14.756 \cdot \ln(AW\ [mm]) + 14.900$$

where an individual is considered mature if $M_{(female)} > 0$.

Sex ratios (proportion female by number) were calculated as:

$$Sex\ ratio = N_{(female)} / (N_{(male)} + N_{(female)})$$

BCD infections of snow crab were first detected in 2008. From 2009-2011, laboratory analysis of haemolymph occurred to monitor actual infection rates within the Scotian Shelf snow crab population. This method was suggested to improve the detection rates as visual assessments are only effective in identifying late-stage infections. Upon critical comparison of the visual and laboratory results of BCD detection, visual assessment was determined to be a more robust method of detection. As such, the laboratory testing of crab haemolymph was discontinued due to high costs (approximately $5 per sample) and unreliable results.

Size-frequency histograms were expressed as number per unit area swept in each size interval (No. km^{-2}; i.e., the arithmetic mean numerical density per unit area). Modes and the bounds of each modal group were identified from size frequency distributions. Through development snow crab moult through several instar stages. Each instar (I) was determined after an analysis of size-frequency distributions to have a lower bound of CW (mm) approximated by (see also Figure 7):

$$CW_{(I,\ male)}\ [mm] = \exp(1.918 + 0.299 \cdot (I - 3))$$

$$CW_{(I,\ female)}\ [mm] = \exp(2.199 + 0.315 \cdot (I - 4))$$

"Viable habitat" for fishable snow crab was modeled from snow crab trawl surveys, snow crab fisher logbook records and research vessel (RV) groundfish surveys. A binomial generalized additive model (GAM) with a logit link function was used with smoothed (thin-plate-spline) covariate functions (R-library "mgcv"; Wood 2006). Statistically significant covariates were determined to be year, week number, northing and easting, depth, bottom slope, bottom curvature, bottom temperature, annual amplitude of temperature fluctuations, the week number at which temperature minima were observed, substrate grain size, species composition (correspondence analysis), species richness and biological productivity indices (figures 8-9, see Choi et al. 2005a for more details on methods). These modeled relationships were used to predict SSE snow crab habitat after discretizing covariate information to a spatial resolution of 1 × 1 km grids (Figures 8, 9). Potential snow crab habitat was identified as those locations where the predicted probability of finding snow crab derived from posterior predictive simulations (Gelman and Hill 2007) was > 0.05 or when the 95% confidence interval of the probability of observing crab did not intersect 0. For 2014, the potential snow crab habitat area was defined as the mean of the estimated habitat area over the past five years, with the fishable biomass estimates calculated as the product of the geometric mean fishable biomass index from the survey and the estimate of potential habitat. The biomass and numerical densities of non-commercial life stages of snow crab were estimated using the geometric mean of the annual snow crab survey stations.

PREDATION

The predators of snow crab were determined using data housed in the DFO Maritimes Region Food Habits Database (Cook and Bundy 2010). This database contains the stomach contents information for more than 160,000 individuals representing 68 ground and pelagic fish species collected from various sources since 1958. There was consistent sampling of diet data in ENS between 1999 and 2014. From this data set, the predators of snow crab were determined, as well as the frequency with which snow crab have been observed as part of the predator species diet and the percent of total weight of stomach contents represented by snow crab . As the impact of predation relates not only to the frequency of the species consumed, but also the biomass of the predator species, the trends in biomass for the identified snow crab predators from both the snow crab survey and the summer DFO R/V groundfish survey (herein groundfish survey) were examined. The biomass indices from the snow crab survey were presented as the geometric mean and bootstrapped confidence intervals of the area and were standardized weight for each tow (expressed as kg / km^2). The groundfish survey uses a stratified random survey design, so the biomass index for this series was estimated as a stratified mean with boot strapped confidence intervals (Smith 1997), estimated as the same density measure, kg / km^2,as the snow crab survey index. The groundfish survey strata used to represent N-ENS were 440-442, S-ENS were 443-467 and 4X were 470-483 (this excludes the outer and inner Bay of Fundy; Figure 10).

STOCK ASSESSMENT MODEL

A modified discrete logistic model of the fishable biomass component is used to determine the relevant biological reference points (i.e., carrying capacity and fishing mortality at maximum sustainable yield, or F_{MSY}) associated with the harvest control rules of the snow crab fishery. However, empirically determined fishable biomass estimates are used in preference over modeled estimates until such a time that more data years stabilize the modeled results. See Appendix 1 for more details of methods. Bayesian state space methods are used to estimate the parameters of this model and associated Harvest Control Reference Points. See Appendix 2 for a general background to the Precautionary Approach (PA) and Sustainability as applied to this fishery.

ECOSYSTEM INDICATORS

A multivariate data simplification method known as multivariate ordination was used to describe systemic patterns in temporal data series (Koeller et al. 2000; Brodziak and Link 2002; Choi et al. 2005a; Koeller et al. 2006). Indicators were made directly comparable by expression as anomalies in standard deviation units (i.e., a Z-score transformation) and then colour-coded. Missing values were coded as white. The metrics were then ordered in the sequence of the primary gradient (first eigenvector) obtained from the ordination. This allowed the visualisation of any temporal coherence in the manner in which suites of these indicators changed over time. The sequence of the indicators reflects the degree of similarity in their temporal dynamics. Specifically, a variant of Principal Components Analysis (PCA) was used that involved an eigenanalysis of the correlation matrices of the indicators, following data-normalisation of those that were not normally distributed ($\log_{10}(x+1)$ transformations were sufficient). In classical PCA, it is customary to delete all such cases (years) with missing values, but this would have eliminated much of the data series from the analysis. Instead, Pearson correlation coefficients were computed for all possible pair-wise combinations with the implicit assumption that it represents a first-order approximation of the "true" correlational structure.

LIFE HISTORY

The snow crab (*Chionoecetes opilio*, Brachyura, Majidae, O. Fabricius) is a subarctic species resident along the east coast of North America from northern Labrador to the Gulf of Maine. In the SSE, commercially fished snow crab are generally observed between depths of 60 m and 280 m and between temperatures of -1°C and 6°C. Snow crab are thought to avoid temperatures above 7°C, as metabolic costs are thought to match metabolic gains (Foyle et al. 1989); though in S-ENS snow crab have been observed above the "break-point" temperature. Snow crab are generally observed on soft mud bottoms, although small-bodied and molting crabs are also found on more complex (boulder, cobble) substrates (Sainte-Marie and Hazel 1992; Comeau et al. 1998).

Snow crab eggs are brooded by their mothers for up to two years, depending upon ambient temperatures, food availability and the maturity status of the mother (up to 27 months in primiparous females – first breeding event; and up to 24 months in multiparous females – second or possibly third breeding events; Sainte-Marie 1993). More rapid development of eggs (from 12 to 18 months) has been observed in other systems (Elner and Beninger 1995; Webb et al. 2007). Over 80% female snow crab on the Scotian Shelf are estimated to follow an annual cycle, rather than the bi-annual cycle observed in most other areas (Kuhn and Choi 2011). A primiparous female of approximately 57.4 mm CW would produce between 35,000 to 46,000 eggs, which are extruded between February and April (in the Baie Sainte-Marguerite region of the northern Gulf of Saint Lawrence; Sainte-Marie 1993). The observable range of fecundity is quite large, especially as multiparous females are thought to be more fecund with more than 100,000 eggs being produced by each female. Eggs are hatched from April to June when the pelagic larvae are released. The pelagic larval stage lasts for three to five months (zoea stages 1 and 2 and then the megalopea stage) during which snow crab are feeding upon plankton. The larvae settle to the bottom in autumn to winter (September to October in the Gulf area). In the SSE, pelagic stages seem to have highest abundance in October and so may begin settling as late as January. Very little is known of survival rates at these early life stages.

Once settled to the bottom (benthic phase), snow crab grow rapidly, molting approximately twice a year (Sainte-Marie et al. 1995; Comeau et al. 1998; Figure 11). The first inter-molt stage (instar 1) is approximately 3 mm CW. After the 5th instar (15 mm CW), the molting frequency declines to annual spring molts until they reach a terminal maturity molt. Growth is allometric with weight increasing approximately 250% with each molt (Figure 7). Terminal molt has been observed to occur between the 9th to the 13th instar in males and the 9th to 10th instar in females. Just prior to the terminal molt, male crab may skip a molt in one year to molt in the next (Conan et al. 1992; Figure 11). Male snow crab generally reach legal size (≥ 95 mm CW) by the 12th instar; however, a variable fraction of instar 11 snow crab are also within legal size. Male instar 12 snow crab represent an age of approximately nine years since settlement to the bottom and 11 years since egg extrusion. Thereafter, the life expectancy of a male is approximately five to six years. Up to ten months are required for the shell to harden (CC1 and early CC2; Table 5), and up to one year for meat yields to be commercially viable. After hardening of the carapace (CC3 to 4) the male is able to mate. Near the end of the lifespan of a snow crab (CC5), the shell decalcifies and softens and may be heavy epibiont growth. In some warm-water environments (e.g., continental slope areas), epibiont growth occurs at an accelerated rate creating some uncertainty in the classification of CC5 crab.

Females reproducing for the first time (primiparous females) generally begin their molt to maturity at an average size of 60 mm CW and mate while their carapace is still soft (early spring: prior to the fishing season in ENS and during the fishing season in 4X). A second mating period later in the year (May to June) has also been observed for multiparous females (Hooper 1986). During mating, complex behavioral patterns have also been observed; the male helps

the primiparous female molt, protects her from other males and predators and even feeds her (indirectly; Hooper 1986). Pair formation (a mating embrace where the male holds the female) may occur up to three weeks prior to the mating event (Hooper 1986). Upon larval release, males have been seen to wave the females about to help disperse the larvae (i.e., prior to a multiparous mating). Females are selective in their mate choice, as is often the case in sexually dimorphic species, and they have been seen to die in the process of resisting mating attempts from unsolicited males (Watson 1972; Hooper 1986). Males compete heavily for females and often injure themselves (losing appendages) while contesting over a female. Larger males with larger chela are generally more successful in mating and protecting females from harm.

ECOSYSTEM CONTEXT

OVERVIEW

An overview of some relevant social, economic and ecological factors is provided here to form a basis for discussion of the place of snow crab in its ecosystem (for more details, see Choi et al. 2005a and Appendix 3). The key environmental, social, economic and fishery-related indicators were identified and summarized in Figure 12.

The first axis of variation accounted for 21.9% of the total variation in the data (Figure 13), and was dominated by the influence of declines in mean body size of organisms in the groundfish surveys; socio-economic indicators of ocean use by humans and associated changes in their relative abundance: landings and landed values of groundfish (declining), invertebrates (increasing), declines in sharks and large demersals and landings of pelagic fish, and oil and gas exploration and development (increasing). Nova Scotia Gross Domestic Product (GDP) and population size were also influential factors that have been increasing. Further, the physiological condition of many groups of fish has been declining as has been the number of fish harvesters in Nova Scotia. The temporal differences along this axis of variation indicates that coherent systemic changes of socio-economic and ecological indicators occurred in the early-1990s, with some return to historical states evident (Figure 13).

Importantly, temperature-related changes were generally orthogonal (independent) to the above axis of variation (not shown). This second (orthogonal) axis of variation, accounting for 10% of the total variation was strongly associated with the cold intermediate layer temperature and volume, bottom temperatures and variability in bottom temperatures, bottom oxygen concentrations and sea ice coverage.

Anecdotal information from fishers and fishery-based catch rates (Figure 4) suggests that the abundance of snow crab was low in the near-shore areas of the SSE, prior to 1980. Increases in catch rates were observed throughout the shelf in the mid-1980s and 1990s in N-ENS and S-ENS, respectively. As commercially exploitable snow crab require at least nine years from time of settlement to reach the legal size of 95 mm CW, their increasing dominance on the shelf must have had their origins as early as the late-1970s and 1980s (N-ENS and S-ENS, respectively). For S-ENS, these timelines are confounded by the expansion of the fishing grounds towards increasingly offshore areas and the exploitation of previously unexploited crab populations. However, most of this expansion was observed in the post-2000 period when TACs and the closely associated landings increased up to six-fold relative to the TACs and landings of the 1990s and a doubling of fishing effort (Figures 2- 3). The catch rate increases observed in the 1980s and 1990s were, therefore, likely reflecting real increases in snow crab abundance.

The possible causes of this change in abundance can be simplistically broken down into the following categories of explanation: connectivity (metapopulation dynamics); environment

(habitat); top-down (predation); bottom-up (resource limitation); lateral (competition) and human (complex perturbations). These will be briefly discussed below.

CONNECTIVITY

In the context of this assessment, connectivity refers to the manner in which various populations are connected to each other via immigration and emigration, also known as metapopulation dynamics. In the case of snow crab, connectivity between populations exists due to two main processes: larval dispersion in the planktonic stages and directed movement during the benthic stages.

Larval Dispersion

The potential for hydrodynamic transport of snow crab larvae from the southern Gulf of St. Lawrence to the SSE and internal circulation on the SSE has been studied by J. Chassé and D. Brickman (Ocean Sciences Division, BIO, DFO; personal communication). Treating larvae as passive particles, simulations suggested that a large numbers of larvae can be transported onto the SSE (especially near Sable Bank and in the shallows further west). The possibility of snow crab larvae entering the SSE from the Gulf of St. Lawrence region and the Labrador current cannot be ignored, especially given no genetic differences are found between all Atlantic snow crab populations (Pubela et al. 2008). Further, planktonic organisms can maintain their position in a single location in even very strong advective conditions via control of vertical migrations. Thus, the degree of larval retention on the SSE, while unknown, can be large.

The following observations also suggest that the SSE population may be acting as an autonomously reproducing system:

- The temporal dynamics of the SSE snow crab population is generally out-of-phase with the cycles seen thus far in the southern Gulf of St. Lawrence. If the SSE was dependent upon the larval drift from the Gulf region, the temporal dynamics of the populations would be in-phase.
- The spatial distribution of Brachyuran larvae (Scotian Shelf Ichthyoplankton Sampling Program (SSIP) in the 1980s; see summary in Choi et al. 2005b, page 14) have been observed to be quite pervasive throughout the SSE with no spatial clines (i.e., no declines in abundance with distance from the Gulf of St. Lawrence area) as one might expect if the source of larvae were solely from the Gulf region.
- A pulse of larval abundance was observed from 1997 to 1999 with peak levels in 1998 (Choi et al. 2005b, page 14). The timing of this pulse is concordant with the growth schedules of the currently expected 'local' recruitment. Approximately nine years would be required to grow from the zoea stages to instar 11/12, the stages in which snow crab begin to molt to maturity in 2007, the same time difference between 1998 and 2007.
- The period in the late-1990s, when high larval production was observed, was precisely the same period in which the abundance of mature males and females on the SSE were at their peak.

The above circumstantial evidence suggests that the snow crab resident on the SSE may be able to function as a self-reproducing system, regardless of inputs from other systems. Even if external sources of larvae do exist, the reproductive potential of the snow crab resident on the SSE proper cannot be dismissed. To this end, the snow crab industry adopted a PA to the conservation of large mature males (i.e., reduced exploitation rates) to allow them to mate with the more rapidly maturing females.

Movement

Spaghetti tags have been applied opportunistically to monitor snow crab movement since the early-1990s. To encourage participation, a reward program exists and an online alternative for submitting the tag recapture information has been developed.

Movement information was primarily limited to recaptures of mature, terminally molted male crab as the current tagging methods do not allow crab to molt. Tag returns are from the male-only snow crab fishery. Results suggest that although crab movements are quite variable the potential connectivity between regions is still high (Figure 14). The movement of immature and female crab is not known and remains a source of uncertainty. Anecdotal information from other regions and fishers suggests seasonal patterns but none have yet been discerned for the SSE.

Since 2004, 18,225 tags have been applied and 1,164 recaptures (6.4%) have been reported (Table 6). An unknown proportion of tag recaptures are not reported. These unreported captures are detrimental to understanding movement patterns and increases the cost per unit of information on movement. For example, if an annual exploitation rate of approximately 20% is assumed, and a (pessimistically) high tagging-related mortality of 50% is assumed, at least 10% of the marked crab would be expected to be recaptured in the next year. Only 6.4% of the marked crab are reported to have been captured across all years. Anecdotal information suggests that fishers do not always report recaptures. Since 2004, there have been 145 individuals who have reported captures and there have been 1086 total captures (Table 7). On average, each person participating has reported seven or more different captures. This supports the belief that other fishers capture tags without reporting them.

Of the 1,164 tags recaptured, 616 are known to have been returned to the water and 78 of these have been captured again at least once. Tracking crab over multiple captures will give further insight into their movement and possibly help to provide a better idea of movement patterns over the life of the crab. When subsequent recaptures are reported, all people who previously captured that particular crab are notified of the additional movements in a report.

Crab recaptured within 10 days of initial release are not included in the following summary, as this short-term movement could be influenced by other factors, including water currents moving crab as they settle to the bottom after release. Distances traveled by crab are now estimated using the shortest geospatial distance between release and recapture following the depth contours of 60 to 280 meters, which are general bounds to snow crab habitat use. On average, crab tagged between 2004 and 2014 were recaptured in the season following the tagging event (mean time to recapture was 342 days), with the longest time interval between release and initial capture being 1,736 days (approximately 4 years, 9 months; Figure 15). This crab had moved at least 44 km in that five year period. Very few returns of over two years from tagging are reported. Tagging is done on a vessel while it is directing for crab, so tags are generally applied where fishing effort is high. This, and high natural mortality, may be the reason for the majority of the returns being from crab captured in the same season or the season following tagging.

The locomotory ability of snow crab can be very large, as the average distance travelled was 28 km, with a maximum distance traveled of 308 km (Figure 15). The average rate of movement was 2.49 km/month. These distances and rates are most likely underestimates as the actual distance traveled by the crab will be greater due to the topographical complexity and the meandering nature of most animal movement. On average, crab captured in N-ENS have a shortest path movement rate of 3.26 km/month, slightly higher than S-ENS (2.12 km/month). In 4X, the displacement rate is slightly lower than S-ENS at 1.70 km/month (Table 8). However, in some areas, there are small sample sizes, high variability and likely temporal changes in movement rates. In 2014, the shortest path movement from all areas was 5.84 km/month

compared to 3.91 km/month in 2013 and 2.69 km/month in 2012. The higher movement rate in 2014 reflects the decrease in days to recapture rather than greater distances moved. There does not appear to be a pattern of preferred direction of overall movement for tagged snow crab. Patterns of directional movement are most apparent in N-ENS between different years, though these may reflect relative changes in fishing location patterns rather than the actual movement of crab, as the majority of recaptures are obtained during commercial fishing activities (Figure 14).

From 2004-2014, movement between N-ENS and S-ENS was seldom observed. In total, 2 crab tagged in N-ENS were captured in S-ENS and 8 crab tagged in S-ENS were captured in N-ENS. The numbers of returns from fishers in the Glace Bay Hole have increased since 2012, however, total participants in all areas remains low. Fishing pattern, water movement, relative abundance levels and predator and prey fields may all effect the movement between and even within a given management area.

Returns from crab tagged between 2010 and 2014 suggest significant movement from N-ENS into the southern Gulf of Saint Lawrence (sGoSL, Figure 14). The apparent unidirectional nature of this movement (from N-ENS to sGoSL) is confounded by the fact that there has been no tagging program in the sGoSL region in recent years (M. Moriyasu, personal communication). As such, the true degree of connectivity between the Gulf and N-ENS is still unknown, and may be important given the high catch rates of snow crab in the adjacent Area 19 (M. Moriyasu, personal communication).

Acoustic tagging program has been initiated to gain further insight into the movement patterns of crab in N-ENS irrespective of fishing effort. In the summer of 2013, 27 acoustic tags were deployed in N-ENS. Ten of these tags have since been detected on the Cabot Strait Line and two of these were later found within the Gulf region (Figure 16). This further demonstrates the connectivity between the sGoSL and N-ENS. It is hoped that these animals will be returned to the water immediately after capture so that their movement can continue to be studied. An effort will be made in 2015 to tag snow crab in the sGoSL region to determine if the movement is bidirectional.

Within S-ENS, from 2004 to 2014 movement between CFA 23 and CFA 24 has been observed, however, there does not seem to be any substantial net gain or loss between these areas. Higher opportunistic tagging on the CFA 23 side of the CFA 23-24 line, and the proximity of the tagging event to the 23-24 line, can explain any apparent movement out of CFA 24 (Figures 1 and 14).

It is believed that reporting of tags recaptured in 4X is much higher than other areas. Of the 360 tags deployed in 4X since 2011, 76 (21%) have been captured once. Of these, 24 (35%) were captured a second time and 8 (33%) of the 24 were captured a third time. Also, one of these crabs was captured six times after being tagged. There has yet to be any substantial movement observed between 4X and S-ENS. Multiple recaptures, high return rates and seemingly low inter-area movement in 4X over the past few years may lead to better estimates of mortality and movement in this area.

It is recommended that captured tagged crab be released immediately with the tag still attached after relevant data are recorded (date, location, depth, condition of crab, as well as information about the vessel and individual who recaptured the tag). To view the movement data in more detail go to ENS Snow Crab website and click on the tagging tab.

ENVIRONMENTAL CONTROL (HABITAT)

Known environmental (abiotic) influences upon snow crab include substrate type, temperature variations, and oxygen concentrations. Altered temperature conditions over extended periods of time have been observed in the SSE (Figures 12, 17, 18 and 19). For example, prior to 1986, the Shelf was characterized by relatively warm bottom temperatures, low volume of the cold intermediate layer, and a Gulf Stream frontal position closer to the continental shelf. The post-1986 period transitioned to an environment of cold bottom temperatures, high volume of the cold-intermediate layer, and a Gulf Stream frontal position distant from the shelf. The principal cause of the cold conditions is thought to have been along-shelf advection from both the Gulf of St. Lawrence and southern Newfoundland, and local atmospherically-induced, cooling. In the southwestern areas (Emerald Basin), the offshore warm slope water kept subsurface temperatures relatively warm throughout the 1980s and 1990s, the exception being in 1997-1998, when cold Labrador Slope Water moved into the region along the shelf break and flooded the lower layers of the central and south western regions. While this event produced the coldest near-bottom conditions in these shelf regions since the 1960s, its duration was short, lasting about one year.

Juvenile crab (approximately instar 5, or two years since settlement) were already present in high numbers in the transitional year of 1986. These crab were, therefore, the benefactors of environmental amelioration; that is, some other factors(s) had allowed their larval and adolescent numbers to increase prior to these large environmental changes. What these factors(s) are is not yet fully understood, but the reduction in predation mortality associated with the demise of groundfish may be an important hypothesis. Further, it is important to note that bottom temperatures in the distributional centres of S-ENS snow crab have been increasing consistently since the early-1990s (Figures 17 and 18), while snow crab continues to dominate the bottom environment in S-ENS, somewhat weakening the validity of the temperature-hypothesis. The orthogonal nature of the second major axis of the ordination of ecosystem indicators that was dominated by climatic indicators suggests that climatic variation may not be the direct cause of the changes observed in the SSE in the early-1990s (Figure 12).

The discussion of surface area for potential snow crab habitat is limited to the year ending in 2013, as results from 2014 are not available (Figure 20). Overall, the potential snow crab habitat in the SSE for 2013 was above the long-term mean, although all regions showed decreases from 2011, largely due to the warm water influence which persist into 2013-2014 (Figures 17-19). In N-ENS, the surface area of predicted snow crab habitat has varied between 4.9 and 9.2 $\times 10^3$ km^2 and in 2013 was higher than the long-term (1998-2012) mean, despite a decrease from the high in 2011. For S-ENS, the surface area of potential habitat has varied with similar oscillations, ranging between 45 to 95 $\times 10^3$ km^2 and in 2013 was higher than the 1998-2011 mean, albeit lower than 2011 potential habitat area. In 4X, the southern-most limit of the distribution of snow crab, potential habitat has been variable, ranging from near zero to 25 $\times 10^3$ km^2, and has recently dropped rapidly with the strong warming event in 2012, which did rebound for 2013.

TOP-DOWN CONTROL (PREDATION)

Top-down influences refer to the role of predators in controlling a population (Paine 1966; Worm and Myers 2003). The capacity of predatory groundfish to opportunistically feed upon snow crab, in combination with their numerical dominance prior to the 1990s, suggests that they may have been an important regulating factor controlling the recruitment of snow crab. For example, snow crab in the size range of 5 to 30 mm CW (with a 7 mm CW mode; that is instars 2 to 7, with instar 7 being strongly selected) were targeted by thorny skate and cod (Robichaud et al. 1991). Soft-shelled males in the size range of 77 to 110 mm CW during the spring molt were

also a preferred food item. The demise of these predatory groundfish in the post-1990 period, and the resultant release from predation upon the immature and soft-shelled crabs, may have been an important determinant of the current rise to dominance of snow crab in the SSE.

The known predators of snow crab in the SSE were, in order of importance: Atlantic halibut (*Hippoglossus hippoglossus*), Atlantic wolfish (*Anarhichas lupus*), skates (smooth skate *Malacoraja senta*, thorny skate *Raja radiata*, and winter skate *Leucoraja ocellata*), longhorn sculpin (*Myoxocephalus octodecimspinosus*), sea raven (*Hemitripterus americanus*), Atlantic cod (*Gadus morhua*), white hake (*Urophycis tenuis*), American plaice (*Hippoglossoides platessoides*), and haddock (*Melanogrammus aeglefinus*). The level of predation on snow crab appears to be negligible on the SSE as only Atlantic halibut, Atlantic wolfish and smooth skate have snow crab observed in more than 1% of the stomachs sampled (Table 8) which constitutes less than 2.2% of diet by weight within each species, particularly to compared to other regions where the frequency of observing snow crab as prey is often greater than 10% (Robichaud et al. 1989, 1991).

Atlantic halibut biomass indices are increasing across both surveys, particularly in S-ENS, suggesting that the total number of snow crab consumed may be increasing in relation to this predator. This additional source of mortality should be examined more thoroughly (Figures 21 and 22). Atlantic wolfish are second in order of importance as a potential snow crab predator, however, their biomass indices suggest that they are currently at low levels across all areas (Figures 23 and 24). The status of thorny, smooth and winter skates are uncertain, as the two survey trends show somewhat different patterns, which is likely reflective of the differences in trawl efficiency (Figure 25 and 30). If it is presumed the snow crab survey is more reflective of predators in snow crab habitat, the biomass of thorny and smooth skate may be greater across all areas than previously thought. In contrast to many other areas Atlantic cod do not appear to be a strong predator of snow crab (Bailey 1982; Lilly 1984; Robichaud et al. 1989, 1991, Table 8). Moreover, the cod populations on the SSE are currently at reduced biomass index levels in all regions relative to historic levels (Figures 31 and 32), however, there may be some slight increases in S-ENS (cfasouth; Figure 31).

The only predator species that strongly co-associated with snow crab based on their abundance were American plaice, likely due to the difference in habitat preferences of the other predator species (Figure 33). Due to the American plaice's small gape size and mode of feeding, they will only be capable of consuming early instar snow crab. Overall predation mortality from groundfish does not currently appear to be a large source of mortality for snow crab on SSE.

Reports of snow crab predation by squids, seals and other crabs have been made (Bundy 2004), however, their relative impacts are not known. Certainly, in the inshore areas of the Scotian Shelf, the anecdotal information that extremely high densities of these early stage snow crabs are found in lobster traps indicates some degree of habitat overlap with adult lobsters. This suggests that one hypothesis for the current increase in lobster abundance in ENS may in part be related to the food base that the juvenile snow crab represent to lobsters. Predation levels upon small immature crabs are also likely to be on the rise in certain offshore areas. High local densities of these more traditional groundfish are found in areas where small immature crab are found in high densities.

Seals are considered by fishers to be a potential predator of snow crab, and their continued increase in abundance (Figure 12) is a source of concern for many fishers. While they have on occasion been observed with snow crab in their stomachs, it should also be emphasized that some of the highest concentrations of snow crab are currently found in the immediate vicinity of Sable Island, an area where the abundance of grey seals is extremely high. The actual evidence indicating that seals have a negative influence upon the snow crab population,

therefore, seems to be minimal. In fact, it is quite possible that seals and other marine mammals may be having a positive influence by physically importing food and food waste (Katona and Whitehead 1988) from other more outlying areas to the immediate vicinity of Sable Island, so indirectly "feeding" the snow crab and also removing potential predators of crab (in both early pelagic and benthic stages).

BOTTOM-UP CONTROL (RESOURCE LIMITATION)

Bottom-up influences refer to changes in a population due to resource (food) availability. Diet studies and field observations (Hooper 1986) indicate that the primary food items of larger (mature) crab are, in order of importance: echinoderms, polychaete worms (*Maldane* sp., *Nereis* sp.) and other worm-like invertebrates, detritus, large zooplankton, shrimps, smaller juvenile crabs (rock crab, *Cancer irroratus*; toad crab, *Hyas coarctatus;* lesser toad crab, *Hyas araneus*), ocean quahog (*Artica islandica*), bivalve molluscs (e.g., *Mytilus edulis, Modiolus modiolus*), brittle stars (*Ophiura sarsi, Ophiopholis aculeata*) and sea anemones (*Edwardsia* sp., *Metridium senile*). Smaller snow crab have been observed to feed upon, in order of importance: echinoderms, polychaete worms, large zooplankton, detritus and bivalves (e.g., *Mytilus edulis, Modiolus modiolus, Hiatella arctica*). Studies have also demonstrated that cannibalism is also highly prevalent in intermediately sized (morphometrically) mature female crabs (Sainte-Marie and Lafrance 2002; Squires and Dawe 2003).

Most of these food items are part of the detrital food web, and so the proliferation of snow crab under the hypothesis of bottom-up control would be indicative of the proliferation of the detrital subsystem (potentially at the expense of the other parts of the shelf ecosystem, including that of the demersals). This hypothesis is consistent with what is known of the current structure of the SSE (Choi et al. 2005a):

- Phytoplankton abundance in the most recent decade (1991-2001) was considerably higher and more variable than in the 1960s and early-1970s. This likely resulted in increased sedimentation of organic matter to the ocean bottom (Choi et al. 2005a; Figure 12).
- The recent proliferation of northern shrimp (*Pandalus borealis*), another detritivore and also a potential food item of snow crab (Figures 12-34) was co-incident with the rise in abundance of snow crab.
- The demise of the groundfish that would competitively feed upon benthic invertebrates (Figure 12).

Certainly the rapid rate of increase in abundance of snow crab would seem to indicate that resource competition was not a limiting factor (up to the late-1990s).

Near the ocean surface, there has been a trend towards increased ocean colour, an index of chlorophyll concentrations. Therefore, total primary production may be increasing (in the form of diatoms and dinoflagellates). This is likely enhanced by the reduction in abundance of *Calanus finmarchicus,* an important zooplankton link in the pelagic food web.

The distribution of northern shrimp on the Scotian Shelf appears to remain broad (Figure 34) and stock assessment results suggest that the SSE stock is in a healthy state (DFO 2012).

LATERAL CONTROL (COMPETITION)

Lateral (and internal) influences refer to the competitive interactions with groundfish, other crab species, cannibalism and reproduction-induced mortality (direct and indirect). The diet of snow crab overlap in many ways with that of some groundfish species; thus, the demise of these

groups in the late-1980s and early-1990s would have been doubly beneficial to snow crab through the reduction in predation pressure and also resource competition. The spatial distribution of snow crab overlaps with that of basket stars, sea cucumbers, sand lance, capelin and toad crab. Some of these species may be competitors of snow crab for food and habitat space. There were no strong negative relationships between snow crab and other bycatch species (Choi and Zisserson 2012), suggestive of little competitive interactions. The potential competitors, lesser toad crab and Jonah crab, remain in relatively patchy distributions and, therefore, do not currently appear to pose much threat to the overall health of the snow crab stock (Figures 35 and 36).

DISEASE

Bitter crab disease is observed in crustaceans throughout the world, though most-commonly in the northern hemisphere (Stentiford and Shields 2005). The name arises from the bitter (aspirin-like) taste, which infected animals exhibit once cooked, rendering them unmarketable. Bitter crab disease infections in snow crab have been observed in Alaska, Newfoundland, Greenland, and most recently on the Scotian Shelf (Morado et al. 2010). In Atlantic Canada, BCD infected snow crab were first observed in Bonavista Bay in 1990 (Taylor and Khan 1995), though the range of infection now extends from southern Labrador to the southern Grand Banks. Infected animals are rare on the southern and western coast (Dawe et al. 2010) of Newfoundland in the waters most proximal to the ESS. Salinity levels and water temperature, as well as ocean currents (affecting the distribution of both crab larvae and the water-borne *Hematodinium*), are potential limiting factors of disease prevalence (Morado et al. 2010). Infected snow crab were first observed on the Scotian Shelf in the 2008 snow crab trawl survey, with a handful of anecdotal reports of infected crab having been seen in the commercial catch in the near-shore areas previous to 2008. The fall survey timing is advantageous to detection as animals infected during the spring molt are expected to show visible signs of infection by the fall. Visible identification of infection can be confounded by examination of infected animals in early stages of (not yet showing visible) infection earlier in a given year.

This disease is caused by a parasitic dinoflagellate of the genus *Hematodinium*. It infects an animal's haemolymph (blood), gradually dominating the animal's haemolymph and resulting in reduced numbers of haemocytes in the blood and the ability of the organism to transport oxygen. Infection appears to take place during molting, and virtually all infections appear to be of animals that have molted within the past year (new shell). As such, there is a high likelihood of infection in juvenile animals as they molt frequently. It is not known if animals infected with *Hematodinium* will always develop the disease. It is considered fatal and assumed to kill the host organism within a year. Infected animals appear lethargic or lifeless, and they have a more reddish ("cooked") appearance, dorsal carapace with an opaque or chalky ventral appearance, and a milky haemolymph appearance. Depending on the severity of the infection, it is readily identified visually and can be confirmed through the use of a Polymerase Chain Reaction (PCR) laboratory assay performed on an alcohol-fixed haemolymph sample from the infected animal or microscopically of stained haemolymph smears.

The number of visibly infected animals has remained constant and at low levels with prevalence rates near 0.1% (Table 9). Crab of both sexes have been observed with BCD in all areas (Figure 37) across a wide range of sizes (20-100 mm CW; Choi and Zisserson 2012), though, generally, in immature animals. Indeed, mature, older-shelled crab infected with BCD have yet to be observed in the region. This suggests that infection may be linked to molting and that it increases mortality rates substantially.

HUMAN INFLUENCE

The human influence is a quite complex mixture of the above controlling influences exerted both directly and indirectly upon snow crab. Directed fishing for snow crab is discussed in the next section (fishery assessment). Here, other forms of human influences are discussed.

Bycatch of Snow Crab in Other Fisheries

The spatial distribution of northern shrimp (*Pandalus borealis*) largely coincides with that of snow crab, and so this fishery represents a potential source of additional snow crab mortality through incidental bycatch. The use of trawls by the shrimp industry is of particular concern as they can cause co-incident damage of snow crab, especially those susceptible to crushing, such as crab in newly molted soft-shelled stages. This is particularly relevant as areas with high shrimp fishing activity are the same areas with the highest catch rates and landings of snow crab. The inshore lobster fishery may also represent a source of juvenile and adult female snow crab mortality in some areas, as anecdotal reports suggest capture in lobster traps and (illegal) use as bait. This has been stated by fishers to be more prevalent in 4X as well as some limited areas along the southeast coast of Nova Scotia during the early part of the lobster season in April. This bycatch of snow crab in the lobster traps generally occurs only when cold bottom water temperatures coincide with lobster fishing efforts in near-shore areas. Additionally, bycatch of snow crab in Danish seines has been anecdotally reported from the limited flatfish fisheries on the Scotian Shelf.

Bycatch of Other Species in the Snow Crab Fishery

At-sea-observed estimates of bycatch of other species in the commercial catch of the SSE snow crab fishery can be extrapolated to the entire fleet based on landings and the proportion of landings observed (Tables 10 and 11). In ENS, a total of 12,046 t of snow crab were landed in 2014 with associated estimates of bycatch at 0.02 t. Though bycatch rates in ENS are traditionally very low (~0.01%), the 2014 value is well below normal levels. There has been no change in sampling protocol or fishing practices that would explain this sudden decline in bycatch rates.

CFA 4X had a total estimated bycatch of 1.7 t associated with 79 t of snow crab landings (2.2%). CFA 4X traditionally shows higher (relative to ENS) bycatch rates due to lower densities of commercial snow crab and a higher species diversity in some of the fishing grounds. In 2013 and 2014, 4X bycatch rates were unusually high (relative to past seasons) due to very low catch rates and increase in searching to locate commercial snow crab. These search activities increase fishing effort in non-traditional fishing grounds with higher densities of species other than snow crab.

The low incidence of bycatch in commercial catch of the SSE snow crab fishery can be attributed to:

- Trap design – top entry conical traps excludes many fish species.
- Passive nature of fishing gear as opposed to other gear types, such as trawl nets (also increases survival of bycatch discards).
- Large mesh-size of trap netting (at a minimum 5.25" knot-to-knot).

The majority of bycatch for all areas is composed of other invertebrate species (e.g., northern stone crab and American lobster) for which higher survival rates can be expected after being released, as compared to fin fish discards. In the three year record, observers reported two leatherback turtles as having been entangled in buoy lines (2012 and 2013). These turtles were both reported to be released alive in a timely manner. Additionally, a humpback whale was

observed entangled in buoys lines in 2012, and this animal was released with very minimal damage (slight lacerations around tale area from rubbing of ropes), with a small amount of rope still attached loosely to the whale. The crew of the vessel "did everything in their power to remove the whale from the gear without harming it" (Javitech Ltd., personal communication).

Oil and Gas Exploration and Development

Oil and gas exploration and development has and continues to occur on the Scotian Shelf near to, or upstream of, major Snow Crab fishing grounds and Snow Crab population centers in both N-ENS and S-ENS. Seismic surveys are used by the oil and gas industry to identify areas of petroleum resource potential beneath the seafloor (Breeze and Horsman 2005). The effects of offshore oil and gas seismic exploration on potentially-vulnerable components of the Snow Crab population (e.g. eggs, larvae, and soft-shelled crab), as well as on the long-term biological development and behaviour of this long-lived species, are still not known (DFO 2004; Boudreau et al. 2009; Courtenay et al. 2009). However, anecdotal evidence following seismic exploration that occurred in November 2005 over the Glace Bay Hole and the shallows of the Sydney Bight (i.e. Hunt Oil 2005), where immature and female crab are generally abundant, suggested that seismic may have impacted the Snow Crab population proximal to the exploration program. The Canada-Nova Scotia Offshore Petroleum Board (CNSOPB), the regulator that oversees the petroleum industry that operates in the offshore of Nova Scotia, may issue Call for Bids for offshore exploration in N-ENS and S-ENS in 2016 and 2017, as part of its current three year plan (CNSOPB 2015). Future seismic exploration in offshore areas occupied by Snow Crab may need to evaluate the impacts on the species.

Undersea Cables

Undersea cables have been identified by fishers as another source of concern, in particular, the Maritime Link subsea cables in N-ENS. Two subsea High Voltage DC Cables will span approximately 180 km from Cape Ray, Newfoundland, to Point Aconi, Nova Scotia (Emera 2013), to transport electricity from the Lower Churchill Hydro-electric project. These cables, are currently planned to be laid directly through the most productive snow crab fishing grounds of N-ENS (Figure 38) and will be spaced by up to 200 m. They may create a barrier to normal snow crab movement through static magnetic fields (and/or associated) induced electrical fields, increased temperature (generated by the resistance of flow through cables) or as direct physical barriers created as a result of trenching activities and substrate disturbance. At present, there is no information that can be presented to definitively describe their effects upon snow crab. Additional tagging effort has been undertaken in this area in 2013 and 2014 (see above section on Movement) and will likely continue for the next several years. It will be useful to understand the natural movements of snow crab into and out of this area prior to the installation of the undersea cable.

Socio-Economics

A coherent change in many socio-economic indicators occurred in the mid-1990s, in the same time frame as the large-scale changes in the Scotian Shelf ecosystem (Figure 12). In general, the demographics of Nova Scotia shifted toward an older and more affluent population base with the ageing of the "baby-boomers". The total population size has also been increasing over the historical record to approximately 943,000 people in 2014, as well as a trend toward a population with higher levels of education. Nova Scotia's GDP has also been increasing along with the GDP associated with oil and gas exploitation and the number of cruise ships visiting Halifax. These demographic changes are associated with a greater biological demand for fishery resources, locally and as exports.

Amongst the more fishery-related indicators, there has been an increased importance of invertebrate fisheries with the demise of the groundfish in the early-1990s, both in terms of total landings and landed values of the fisheries. The number of shell-fish closures has increased over time. However, the relative importance of fishing to the Nova Scotia GDP and the total number of fish harvesters has both been on the decline.

The fished species have changed greatly since the early-1990s in conjunction with the rapid changes in species dominance structure. Since this time, total groundfish landings have declined, falling from 281 kt in 1991 to 59 kt in 2006 for the province of Nova Scotia. Similarly, the pelagic fish landings have decreased from 125 kt in 1990 to 54 kt in 2008. In contrast, invertebrate landings have increased from 111 kt to 179 kt since the 1990s as has the total landed value for all fisheries combined, increasing from $445 million in 1990 to $845 million in 2013.

The links between the socio-economic changes observed and the changes in the Scotian Shelf ecosystem are complex. However, an important issue to consider is whether alterations in social and economic structure can assist in the continued evolution of precautionary and ecosystem-based management of a sustainable and viable snow crab fishery. Certainly, transparency in management, communication by science and a unity of voice of fishers with a long-term vision for their resource can definitely assist, as has been the experience in S-ENS in the post-2004 period – a success that merits emphasis. Maintaining and fostering these positive determinants of stewardship is essential for the continued social, economic and ecological sustainability of this fishery.

Marine Protected Areas

St. Anns Bank area has been identified as an Area of Interest (AOI) for designation as a Marine Protected Area (MPA) pursuant to the *Oceans Act*. The outcomes of this designation are still to be determined and likely to be complex. The presence of a refuge from fishing activities is always positive as it serves as a fallowing area. However, if the protection is disproportionately beneficial to other organisms, be they predators of snow crab or prey items, the effects upon snow crab can be mixed. The long-term effects of an AOI/MPA cannot be determined at this point.

FISHERY

Effort

In N-ENS, a spring season was introduced in 2008 in an effort to reduce soft and white crab capture and handling, and now represents the majority of the fishing efforts. This season was in addition to the traditional summer season and individual fishers are able to fish during either (or both) seasons. After a successful trial in 2008, landings associated with spring fishing efforts peaked at 91% in 2010 and had remained above 70% of landings since that time. Only 53% of N-ENS landings in 2014 were from the spring fishery (Figure 39). This was due in large part to sea ice being resident in this area much later than usual. The 2014 fishing effort (Figure 40) was focused on the trench of deep water located along the north-eastern coast of Cape Breton ("inside") with some resurgence of efforts in the Glace Bay Hole, particularly during the summer season. Since 2012, no fishing has occurred on the northern-most portion of N-ENS along the CFA 19 line as had occurred in previous seasons. This is potentially associated with strong tides confounding fishing efforts during the spring season. The number of vessels active each season in N-ENS remains relatively constant at approximately 60 vessels since 2009 (Figure 41).

In S-ENS, fishing effort continues to be focused on offshore fishing grounds in both CFAs 23 and 24 (Figure 40). Much of the fishing effort in CFA 23 still continued to be focused on the holes found between Misaine and Banquereau banks, though additional effort was observed in the inshore/ mid-shore "bad neighbours" area particularly during the spring as compared to past seasons. There was an almost complete absence of effort in the western-most portion (along the "Eastern Shore") of CFA 24 (west of 61.5° Longitude). CFA 24 showed a similar fishing pattern to the previous year with spring fishing occurring primarily north of Sable Island and around Canso Bank, though more spring fishing effort occurred southeast of French Bank. Increased summer fishing activity occurred in the near shore area of CFA 24 as compared to the previous year.

In both CFAs 23 and 24, fishing patterns were affected by an overlap with spring fishing activities for shrimp as the snow crab fleet has limited access to some of the most productive snow crab fishing zones throughout the spring months, due to area closures ("shrimp boxes"). When these areas open to the snow crab fleet in the early summer, the majority of fishing effort occurs within these shrimp boxes. Previous to 2010, less than 20% of S-ENS landings occurred prior to July 1st, whereas now over 60% of total landings consistently occur in this spring period. CFA 24 consistently shows a higher percentage of spring landings as compared to CFA 23 (Figure 39).

In both CFAs in S-ENS, there has been a continual decrease in the number of active vessels in the past four years (Figure 41). This is due to many licenses partnering and license holders choosing to lease their quota for the year rather than fishing it themselves. This raises concerns when hired captains and crews potentially have no long-term stake in this fishery. Such individuals may not follow proper handling protocols for discarded crab, fish in strategic ways to avoid soft-shelled crab capture and choose not to report tagged crab essential to proper movement studies. The vessel chosen to fish a license holder's quota may be driven by price, with perhaps less concern for experience of the captain and crew and their regard for conservation-minded harvesting.

In 4X, the fishing effort was focused on two main areas: south of Sambro and west of Roseway Bank with some limited effort south of Lunenburg (Figure 40).

In 2014, a total of 7,393 and 100,218 trap hauls were applied in N-ENS and S-ENS, respectively. In 2013/2014, a total of 5,101 trap hauls were applied in 4X (Tables 2-4; Figure 2).

Landings

Landings in 2014 for N-ENS and S-ENS were 778 t and 11,267 t, respectively, and they were 79 t in 4X for the 2013/2014 season, representing a decrease of <1 % (N-ENS) and decreases of <1% (S-ENS) and 33% (4X) relative to the previous year (Figures 3 and 42). Total Allowable Catches in 2014 were 783 t, 11,311 t and 80 t in N-ENS, S-ENS and 4X, respectively. As in 2013, an increase in the total landings coming from the near-shore regions of S-ENS was noted for 2014 as compared to the previous number of years (Figure 42).

Catch Rates[1]

Non-standardized catch rates in 2014 were 104 kg/trap haul in N-ENS, 112 kg/trap haul in S-ENS, and 15 kg/trap haul in 4X in 2013/2014 – which relative to the previous year represents a decrease of 2%, an increase of 8% and an increase of 25%, respectively (Figure 4; tables 2-4).

[1] Please recall the caveats about catch rates being inappropriate indicators of fishable biomass, as discussed in the Methods section above.

In N-ENS, the 2014 catch rates were 104 kg/trap, a decrease relative to 2013 (106 kg/trap). N-ENS catch rates remain well above the 10 year mean (69 kg/trap; Table 2; Figure 4). Catch rates in N-ENS appeared to increase from northwest to southeast (Figure 43) with localized highs in the Glace Bay Hole area. In the past, catch rates in N-ENS were often quite variable within the entire area with pockets of high or low catch rates. Catch rates in N-ENS are now similar to those observed in S-ENS. Catch rates from the summer fishery (Figure 43) were somewhat higher than those experienced in the spring fishery in 2014. In both spring and summer N-ENS fisheries, catch rates declined over the course of the short season. It is important to note that the maintenance of high catch rates in N-ENS is less a consequence of stable numeric abundance but rather through increasing mean size of crab in the catches (Figure 45).

In S-ENS, the 2014 catch rates were 112 kg/trap, an 8% increase relative to 2013 and above the 10-year mean of 101 kg/trap (Table 3; Figure 4). Catch rates increased in each of the two CFAs in S-ENS, CFA 23 and CFA 24, with CFA 23 showing relatively higher catch rates than CFA 24. Catch rates were uniformly moderate throughout the majority of the exploited fishing grounds in S-ENS, with the localized high catch rates in the Bad Neighbours Shoal area along the 23/24 line and in the holes between Misaine and Banquereau banks (Figure 44). The lack of very low localized catch rates suggests that fishers were efficiently identifying high abundance locations and, therefore, generally avoiding over-depletion of lower abundance areas. Limitations on access to all fishing grounds caused by temporal exclusions ("Shrimp Boxes") may lead to short-term localized depletion in available fishing grounds during spring fishing activities. Examination of weekly catch rates over the course of the 2014 season (Figure 43) shows a strong decreasing trend in catch rates in CFA 23 over the initial half of the season, with a marked resurgence with the opening of the "shrimp boxes" and a declining trend after that time. However, CFA 24 shows a relatively stable catch rate over the first half of the season with a general declining trend over the latter half of the season. This would suggest that CFA 23 catch rates are more affected by limited access to fishing grounds caused by seasonal closure of the "shrimp boxes". It is important to note that in all areas it is common to see a strong divergence in catch rate from the trend during the final weeks of the season. This is assumed to be caused by the almost complete lack of effort and landings during this time.

In 4X, the 2013/2014 catch rates were 15 kg/trap (Table 4; Figure 4), an increase of 25% from the 2012/2013 catch rate, though well below the 10-year mean on 25 kg/trap. The 4X catch rates are consistently well below those of N-and S-ENS, even for the 2005-2008 low abundance period in N-ENS. Weekly catch rates in 4X (Figure 43) generally show an oscillating pattern over the course of the season. This oscillation is most likely caused by varying amounts of effort as most fishers shift their efforts away from snow crab for the lobster fishery in late-November and return to snow crab fishing in mid-January. Localized warming and cooling of waters caused by weather patterns are believed by many fishers to further exacerbate these fluctuations in catch rates. With approximately 25% of the 2014/2015 TAC, catch rates appear to have rebounded to above the 10-year mean, though cannot be considered as comparable until the entire TAC has been reached for the season.

At-sea-observer Coverage

In N-ENS, the at-sea-observer coverage was just above the target level of 5% of the TAC, at 5.2% (Figure 5). A total of 311 trap hauls were observed (approximately 4.2% of commercial trap hauls). In S-ENS, 4.2% of the TAC was observed (with a target level of 5%). A total of 4,469 traps (approximately 4.4% of commercial trap hauls) were observed. In 4X, 12.8% of the TAC was observed, relative to a target level of 10%. A total of 648 traps were observed, 12.7% of commercial trap hauls.

Newly Matured (CC1 and CC2) and Soft-Shelled Crab

In N-ENS, CC1 and CC2 crab collectively represented approximately 19% of the total catch (Table 11; Figure 46), relative to 6% in 2013. Much of this increase is likely attributable to increased fishing effort in the summer season as compared to the previous year. As expected, landings during the spring fishery have had negligible collective catches of CC1 and CC2 crab (<1%), whereas this increases to over 30% for the summer fishery. High incidence of soft-shelled crab in the summer fishery has been suggested anecdotally as being a result of localized depletion of stronger, hard-shelled males, and a consequent increased trapability of new-shelled males due to the lack of competition/inhibition. The newly matured animals encountered by the summer fishery did represent an unexpected (based on the previous year's trawl survey results) source of recruitment into the mature segment of the population. There was a decrease in the proportion of the CC4 and CC5 crab in the observed component of the fishery, which also indicated more potential recruitment than predicted.

Low incidence of soft-shell catches (relative to very high levels in 2005-2008) were observed in both the spring and summer fisheries in N-ENS (Figure 47). If one assumes no recaptures and prorates the observed landings to total landings, this amounts to an additional 25 t (3.2% of landings) being discarded as soft crab with potentially high handling-associated mortalities. This is consistent with 3.4% in 2013. A continuation of spring fishing efforts, and shorter summer fishing period, will likely help to control the potential total mortality of soft-shell crab in future seasons. The increased occurrence of CC2 crab without a corresponding increase in soft crab indicates that these animals had hardened beyond the 68 durometer reading yet were still not viable commercial product. Such animals are often referred to as white (rather than soft) crab.

In S-ENS, the occurrence of CC1 crab remains at low (~1%) levels (Table 12; Figure 46). There was an increase in the proportion of CC2 crab from 3.3% in 2013 to 15.9% in 2014. It should be noted that 2013 was an anomalously low year for CC2 crab. This increase may be partially attributable to increased summer (as opposed to spring) fishing. Observed catches of high soft-shell percentage (>20% by count) were rare throughout S-ENS in 2014. When prorating observed landings to total landings in S-ENS, this amounts to a potential additional mortality of 217 t (1.9% of landings, 1.7% in 2013). Voluntary avoidance of areas showing high incidence of soft crab must be adhered to by all members of the fleet if this mitigation is to be effective. Unfortunately, this is not always the case. There is potential miscommunication as quotas are sold through processors and other brokers and fished by individuals that do not own quota personally, and thus, have no long-term stake in this fishery. All individuals involved in every level of the fishery must realize the potential damage caused by handling soft crab.

In CFA 4X, for the 2013/2014 season, CC1 and CC2 crab collectively represented less than 4% of the total catch and are comparable to 2012/2013 (Table 13; Figure 46). The 4X fishery continues to show negligible levels of soft crab and a dominance of CC3 and CC4 crab. The data from 4X are not directly comparable to ENS as their fishing season is differs from that of N- and S-ENS.

Old Crab (CC5)

CC5 crab represented a low proportion of the 2014 at-sea-observed catch in both legal and sub-legal size fractions at less than 2% in all areas (Tables 11-13). Similarly low to undetectable proportions of CC5 crab were observed in the trawl surveys (Tables 14-16).

RESOURCE STATUS

SIZE STRUCTURE

In S-ENS, the presence of small immature male snow crab spanning almost all size ranges (20-95 mm CW) observed by the survey also suggests that recruitment to the fishery is probable for the next four to five years and beyond (Figure 48).

In N-ENS, the distribution of male size crab appears very similar to that of 2013, though with fewer large mature animals. There does remain a persistent gap between 60 and 95 mm carapace width, which will likely result in depressed recruitment for the next several years without an immigration of crab from adjacent crab fishing areas (likely CFA 19 and less likely CFA 23, based on movement studies).

Area 4X shows minimal potential for internal recruitment to the fishery for the foreseeable future, based on size frequency distributions from the trawl survey. Movement is likely an important source of crab in this area and a lack of any commercial fishing effort in the western portion of CFA 24 hold potential benefits for 4X. As always, erratic temperature fields in 4X create strong uncertainties for the future.

Very few mature female crab currently exist in N-ENS though, assuming survival, immature female crab in the area will likely begin to recruit to the mature segment of the population in the next 1-3 years (Figure 49). As with the male crab, S-ENS shows a more stable distribution of female snow crab across all size classes. The mature segment of the female population in S-ENS continues to decline and will also be dependent on new recruitment in the next 1-3 years. Though limited numbers of mature female crab exist in 4X, future recruitment to the mature segment of the female population is doubtful in the next 1-4 years based on the current size distributions. Being downstream of all other crab areas increases the chance of larval settlement in 4X regardless of a resident population of mature females.

Male size frequency distributions in 4X exist in a very erratic state, with less annual consistency as compared to N-ENS and S-ENS. The large temperature fluctuations and the different predator fields associated with the warmer waters in the area, and potential movements with CFA 24, likely result in these unstable size structures. Movement of crab away from traditional locations within 4X, in reaction to such temperature and predation changes, may confound inter-annual survey results.

SEX RATIOS

When the relative number of mature females is high, the possibility of reproductive limitation becomes a conservation issue. This is particularly the case in heavily exploited areas where there is an absence of large mature males able to mate and protect the more rapidly maturing and smaller females. This is observed in the southern Gulf of St. Lawrence, where male limitation is a known issue. Conversely, with very low relative numbers of females (e.g., the extended period observed in the early 2000s throughout the SSE) there is low egg and larval production. What may have caused this extended period of poor reproductive potential in the SSE is not known, especially as this fishery is a male-only fishery. A possible explanation for this may arise from differential predation pressures for males and females, as they are spatially segregated in their immature stages and as they are also sexually dimorphic. Irrespective of the specific cause, extreme sex ratios represent an unhealthy reproductive state and, therefore, a long-term conservation issue.

There is a high likelihood that sex ratios will naturally fluctuate over time (Figure 50). This is because female snow crab of a given year-class will mature two to four years earlier than a

male from the same year-class. Females are also believed to have a shorter mature and total life span. Such natural oscillations will be particularly evident when strong year-classes dominate a population, as has been the case in the SSE. In the SSE, the sex ratios of mature snow crab have oscillated with relatively high numbers of females in 1996 and again in 2007, with a major trough in the early 2000s (Figures 50 and 51). Since 2007, sex ratios of S-ENS and N-ENS snow crab have declined, although, in 2014 N-ENS had a slight increase in sex ratio, which may be more reflective of decreasing male population. In Area 4X current sex ratios of mature crab have dropped below 50%.

The sex ratios of immature snow crab (Figure 52 and 53) are currently, between 20- 55% female on the Scotian Shelf and are increasing in N-ENS. The spatial patterns of the sex ratios are generally distinct between offshore and inshore areas: immature males are found in greater proportion (blue) in most areas in ENS, whereas immature females (red) are found in greater proportion in areas bordered by warm water, such as the western portion of CFA 24 and along the eastern and southwest shore of Nova Scotia (Figure 53). When such spatial segregation is observed, the sexes are likely exposed to differential predation effects. Immature females are likely preyed upon by fish and other macro-invertebrates (including other female snow crab, other crabs and lobster) favouring warmer water habitats. This pattern would be exacerbated by the sexual dimorphism of snow crab, as males grow to be larger and so escape some of the size-dependent predation to which the smaller females would be exposed.

FEMALE NUMERICAL ABUNDANCE[2]

Trends in the number of immature and mature females caught in the trawl surveys has been variable across areas (Figures 54-57). In N-ENS, the density of immature female crab has been increasing since 2009, which continues into 2014 (Figure 54). In contrast, the mature female abundance has been extremely low for the past three years (Figure 56). Provided the immature crab are retained and recruited to the mature female component in the area, there may be an increase in the mature component in the coming years, as was seen during the 2004-2007 period (Figures 54 and 56).

In S-ENS, immature female crab were at historical highs in 2005 and 2010, but decreased between 2010 and 2012. The 2013 survey indicated a leveling off of this decreasing trend of immature female abundance and an increase in 2014 (Figure 54). There has been limited numbers of mature female snow crab in S-ENS for the past seven years and this trend continues into 2014 (Figure 56).

Immature females in 4X have declined dramatically between the extreme high in 2010 and 2013, however, there was an increase in 2014. The mature fraction of the female abundance has also decreased from last year (Figure 56). Most of the mature and immature females are primarily found in shallower areas along the shore of mainland Nova Scotia and in offshore areas of CFA 24 (Figures 55 and 57).

The remnant population of mature female crab in 4X may have decreased considerably into 2014. However, most of the immature and mature females are currently located in small areas throughout the SSE (Figures 55 and 57).

[2] Most categories of snow crab are likely under-estimated as catchability corrections are not applied. Their intended use is, therefore, solely to compare relative trends over time.

FISHABLE BIOMASS

The post-fishery fishable biomass index of snow crab in N-ENS was estimated to be 2,075 t, relative to 3,451 in 2013 (Figures 58 and 59). In S-ENS, the post-fishery fishable biomass index was 40,119 t, relative to 46,203 t in 2013. In 4X, the pre-fishery fishable biomass was 2,059 t, relative to 531 t in 2013/2014. The 4X biomass estimate is highly uncertain, as mentioned above, as only a subset of survey stations were completed in 2014. Within each fishing area the highest fishable biomass densities appeared more concentrated in 2014 compared to 2013 (Figure 60). In 4X, the remaining pocket of fishable crab are in close proximity to the 4X/S-ENS line (Figure 60).

RECRUITMENT

The index of recruitment into the fishable biomass was obtained from the research survey of mature males with CC1 and CC2 and durometer reading <68, and CW >95 mm. Since the onset of the standardized snow crab survey in 2004, recruitment remains at relatively low levels in S-ENS (Figure 61). It has been more variable in N-ENS, with 2013 being among the highest level shown; this decreased in 2014. These recruits in 2013 for N-ENS were likely immigrants from adjacent areas (S-ENS or CFA 19), as the previous years' length frequency histograms for the local stock did not show signs of upcoming recruits, with tagging results suggesting significant movement within the area. Recruitment in 4X has been decreasing since 2010, and is low and variable. Most of this recruitment was observed on the core fishing grounds.

It must be emphasized that as the snow crab survey is conducted in late autumn (since 2002), an unknown and variable proportion of the annual recruitment would have also progressed into the mature fishable biomass or soft-shelled crab component; and the catchability of soft-shelled crab is likely reduced due to their behavior of sheltering in rocky burrows. Thus, the recruitment index is only a partial index that is sensitive to annual variations in temperature, food availability and crowding, factors that control the onset of molting and the speed of shell hardening.

STOCK ASSESSMENT MODEL

The logistic production model shown here is largely used as a heuristic to couple landings and biomass estimates for simplistically describing the productivity of the system (see Appendix 1 for more details). However, for both the N-ENS and S-ENS, the models were relatively well behaved and the three MCMC chains did converge. Posterior distributions for K, r, q and process error (bp.sd) were updated from the prior distributions suggesting the data did inform the model output (Figures 62 -65). The posterior distributions for observation error (bo.sd) were not updated from the prior, however, multiple runs using different prior distributions did not impact the overall results (Figure 66). Estimates of population growth rate, r, were very similar for N- and S-ENS with median values of 0.906 and 0.898 (Figure 63), whereas the carrying capacity for S-ENS (76.3 kt) is more than 10 times higher than for N-ENS (5.72 kt), largely reflecting the differences in area of suitable crab habitat (Figure 62). There were also differences in catchability coefficient (q) for N-ENS and S-ENS with estimates of 0.981 and 0.718 respectively (Figure 64). These differences in q may reflect the ability to survey and accurately describe the stock biomass, which is higher in N-ENS as the density of stations is substantially higher than those in S-ENS (Figure 6). The median estimates of F_{MSY} were 0.453 for N-ENS, 0.449 for S-ENS and 0.48 for 4X (Figure 67).

The logistic production model for 4X did not perform well, and the three chains did not converge, regardless of starting values or priors; as can be seen in the bimodal distribution of process error and q (Figures 64 and 65). The results for 4X should be considered preliminary.

FISHING MORTALITY

In N-ENS, fishing mortality (F) has been estimated to have been in the range of 0.1 to 0.9, peaking in 2004 (Figures 69). In 2014, fishing mortality is estimated to have been above 0.30 and has been increasing over the last several years. A reduction in fishing mortality in 2008 was implemented to reduce soft-shell handling.

Fishing mortality for S-ENS has historically ranged from 0.05 to 0.25, peaking in 2003/2004 (Figure 68). In 2014, fishing mortality was estimated to have been 0.18. Localized exploitation rates are likely higher, as not all areas where biomass estimates are provided are fished (e.g., continental slope areas and western, inshore areas of CFA 24) and there are reports of illegal landings in this area.

In 4X, fishing mortality has historically ranged from 0.2 to >0.4, peaking in 2005 and 2011/2012 (Figures 49-53). In 2013/2014, fishing mortality was 0.08. Realized exploitation rates are likely to be higher, since the computed exploitation rates incorporate biomass from throughout the 4X area and not just the fishery grounds.

NATURAL MORTALITY

Wade et al. (2003) suggested that instantaneous mortality rates for southern Gulf of St. Lawrence snow crab >95 mm CW are within the range of 0.26 to 0.48. For early benthic females stages (i.e., unfished snow crab), instantaneous mortality may be near 1 (Kuhn and Choi 2011). Thus, the magnitude of fishing mortality seems to be generally smaller in magnitude than that of natural mortality. Diet studies (Bundy 2004; see also section: Top-down Control (Predation)), suggest that very few natural predators seem to exist for large snow crabs (i.e., legal sized) in the SSE. This has been particularly the case since the demise of most large-bodied predatory groundfish from the eastern part of the SSE (Figure 12). Although, recent reports suggest an increase in the relative abundance of predators of snow crab these levels remain a small proportion of historic reports (DFO 2014; Figures 21-32). This can especially impact recruiting, juvenile and larval crab and may have been contributing factors for the absence of 40-90 mm CW crab in N-ENS.

Other potential mortality factors include: BCD derived from a parasitic dinoflagellate infection (*Hematodinium sp.)*, which was found to be present in the SSE at low levels since 2008; seals (near Sable Island; although see arguments to the contrary in Ecosystem considerations, above); soft-shell/handling mortality; illegal landings; bycatch in other fisheries (lobster and other crab traps, long-lining, gill-nets, trawling); and activities associated with various other human activities, such as exploration and development of oil and gas reserves and trenching activities associated with sub-sea cable installation.

THE PRECAUTIONARY APPROACH

In the context of natural resource management, the PA identifies the importance of care in decision making by taking into account uncertainties and avoiding risky decisions. This is because natural ecosystems are intrinsically complex and unexpected things can and often do happen (e.g., Choi and Patten 2001). Details on the PA and caveats related to its implementation in the form of simplistic "Harvest Control Rules" can be found in Appendices 1 and 2.

The primary tools of fishery management are the control of fishing catch and effort. Generally, by reducing catch and effort, stock status and/or ecosystem context is expected to improve. While it is well known that this is not always the case (Appendix 2), its usage in DFO has been formalized into the determination of Reference Points and Harvest Control Rules.

REFERENCE POINTS AND HARVEST CONTROL RULES

The 4VWX snow crab population is not at, nor near, any equilibrium state. As a result, the parameter estimates derived from the logistic model provide at best first order estimates of the true biological reference points (see methods; Figures 62-64).

The operational reference points associated with the 4VWX snow crab fishery are as follows:

- **Lower Stock Reference (LSR)**: 25% of estimated carrying capacity.
- **Upper Stock Reference (USR)**: 50% of estimated carrying capacity.
- **Removal Reference (RR)**: not to exceed F_{MSY} (where F is the fishing mortality of the legal sized mature male population and MSY is the theoretical Maximum Sustainable Yield).
- **Target Removal Reference (TRR)**: 20% of the fishable biomass (F=0.22). Secondary, contextual indicators are used to alter harvest rates between 10 and 30% of fishable biomass (FB; F=0.11 to F=0.36).

The Harvest Control Rules (Figure 70) are as follows:

- FB > USR: target exploitation rate of 10% to 30% be utilized, based upon contextual information provided by secondary indicators.
- LSR < FB < USR: target exploitation rate of 0% to 20%, based upon contextual information provided by secondary indicators.
- FB < LSR: fishery closure until recovery (at a minimum, until FB > LSR).

From the logistic model output the current estimates of "carrying capacity" for the fishable biomass of snow crab is estimated to be {and 95% CI}:

- N-ENS: 5.72 {4.13, 8.45} kt
- S-ENS: 76.3 {55.1, 109} kt
- 4X: 2.11 {1.59, 2.86} kt

The estimates of F_{MSY} {and 95% CI} were:

- N-ENS: 0.453 {0.36, 0.55}
- S-ENS: 0.453 {0.35, 0.55}
- 4X: 0.478 {0.38, 0.58}

Estimates for 4X should be considered highly uncertain, due to the brevity of their data series and uncertain nature of their error distributions.

Future research priorities associated with reference points:

Many sources of uncertainty/challenges are associated with these reference points and the underlying biological model:

- The fishery projection model is extremely simplistic and focused upon a limited fraction of the total population; intraspecific and interspecific compensatory dynamics are completely ignored. It is a "tactical" model for short-term projections rather than a "strategic" model for biological description and comprehension of longer-term conservation requirements associated with the PA.
- Large changes in carrying capacity have been observed in the area: pre- and post-collapse of groundfish precludes an expectation of a single K (carrying capacity) estimate with associated reference points.
- Large spatial and temporal variations in recruitment strength preclude simple r-parameter estimation.

- Large spatial and temporal variations in environmental conditions increase uncertainty in abundance indices and preclude any reasonable assumptions of fixed natural mortality/intrinsic rate of increase.
- Strong spatial and temporal variations in predator abundance, especially of pelagic and early (juvenile) benthic life stages of snow crab, preclude a simple assumption of fixed natural mortality/intrinsic rate of increase.
- Cannibalism, especially by mature females upon early benthic stages, results in greater dynamical instability and precludes a constant natural mortality/intrinsic rate of increase assumption.
- Anecdotal sources suggest illegal landings might be large (10-20% of TACs) and variable over time. This is not accounted for.
- Alteration of survey timing from spring (pre-2004) to fall (post-2004). Sampling at different points of annual biological cycles creates variable catchability/bias issues.
- Life cycle is complex.

As a result, the following research priorities exist with regard to formulating more appropriate reference points:

- Describe environmental influence upon biological cycles (molting, mating, and egg production) and integrate into a more biologically reasonable model.
- Refine the fishery model and survey index:
  - Incorporate predators and prey to the fishery model.
  - Incorporate growth and variable r, K parameters.
- Identify core spawning and nursery grounds.
- Refine larval production estimates.
- Describe benthic and pelagic movement/connectivity.
- Describe the role of environment/climate and predator-prey interactions upon pelagic and benthic larval survivorship.

RECOMMENDATIONS

GENERAL REMARKS

1. The capture of soft-shelled crab has been low for the past several seasons. However, it remains an issue requiring continued diligence in the SSE. The timing of fishing efforts can help avoid periods traditionally associated with high captures of soft crab (winter and spring fisheries) In S-ENS, this is not always the case, and timely responses from industry to avoid fishing in areas showing high incidence of soft crab must continue to improve if unnecessary mortality of recruits is to be averted. Since 2010, to encourage rapid avoidance measures, soft-shell maps were implemented as interactive GoogleEarth™ maps that can be found at the ENS Snow Crab website.
2. The longevity of the fishable biomass (and, therefore, the stabilization of the fishery) can be improved by fishing solely upon morphometrically mature crab. The arguments for this approach are as follows:
   a. Fishing mature crab would allow them to mate as the fishing season is generally post-mating season (in ENS, but not 4X). This has the important result of reducing Darwinian natural selection for early maturation, which is a long-term hazard for any fishery that harvests mature individuals.
   b. The capture of immature crab ("pencil claws") reduces the longevity of the fishable biomass directly relative to a mature-only fishery. The time difference is two to three

years as immature crab go through a soft- and white-shelled phases that exclude them from the fishery, and so extends the fishable period by this time.

c. Specifically targeting mature (male) crabs is a more optimal exploitation strategy (CC3 and CC4 crab) in that the fishable biomass is harvested when "ready and maximized". This is because there is a significant weight increase if immature crab are allowed to grow and mature (an increase of 250-400%; Figure 7).

In the 2014 season, some of the >95 mm CW will still be composed of immature individuals (Figure 48). Indeed, these immature crab will become the largest-sized individuals in future catches if allowed to grow and reach terminal molt. They will continue to contribute towards reproduction, population-genetic fitness and represent high quality crab for the industry. Harvesting of this component of the catchable biomass is unwise.

3. Anecdotal reports suggest that illegal fishing activities and mis-reporting of catch is occurring, predominantly in S-ENS. Such activities de-stabilize the "precautionary approach" to resource management and can negate the sacrifices made by the snow crab industry to help ensure the long-term stability of this fishery. This issue could be addressed through open communication, industry pressure on the offending parties and novel approaches to fisheries regulation enforcement, such as forensic accounting and monitoring production of crab processing facilities.

SOUTH-EASTERN NOVA SCOTIA (S-ENS)

The long-term PA adopted by the S-ENS fishers since 2004 appears to be creating increased stability in commercial biomass levels. This stability is an important consideration given the continued uncertainty in world markets and the more volatile state of other Atlantic Canadian snow crab populations. S-ENS population is considered to be in the "healthy" zone (FB > USR, Figure 71). Despite the slight decrease in fishable biomass it continues to be high, and with recruitment expected for at least the next three to four years, there remains considerable scope for flexibility. A status-quo to marginal decrease in TAC is recommended.

NORTH-EASTERN NOVA SCOTIA (N-ENS)

High exploitation rates and limited recruitment caused by handling mortality of soft-shelled crab in the past pushed the N-ENS fishable biomass to historic lows. Over the past three seasons the harvest strategy adopted by fishers in N-ENS has been conservative, with exploitation rates being closer to those adopted in S-ENS. The capture of soft-shelled crab has been nearly eliminated, helping to protect recruitment. Fishable biomass has declined rapidly over the past three years, although the stock remains in the "healthy" zone (FB > USR, Figure 71), it is getting close to the cautious zone. The mature component of the stock in this area does appear to be ageing as there was a significant component of CC4 crab observed during the fishing season. That said, there was some CC2 crab observed during the fishing season. These crab were not evident in the 2013 or previous length frequency data or in the 2014 survey, and, thus, may constitute a migrant event from neighbouring areas. If these recruiting crab remain in the N-ENS area they may constitute an important fraction of the fishable biomass for the next few years as there remains a large gap in the length frequency histogram, suggesting limited local recruitment in the medium to long-term. Based on the biomass trends obtained during the survey a decreased TAC is recommended.

AREA 4X

As Area 4X is the southern-most area of snow crab distribution, existing in more "marginal" environments relative to the "prime" areas of S- and N-ENS, an explicitly PA towards this fishery

is essential. Further, the lower recruitment into the fishable biomass and the large inter-annual temperature variations (especially in 2012) increases the uncertainty associated with this area. Indeed the speculated increases in mortality associated with the warm temperature event in 2012, most likely occurred as all measures of snow crab productivity decreased in the area. The 2012/2013 fishery landed approximately 45% of TAC, which resulted in a decrease in TAC for 2013/2014 to 80 t. In the past, S-ENS has been assumed to provide a buffer for 4X via immigration as evidenced by a large portion of 4X's commercial biomass being proximal to the S-ENS line. At present, fishable biomass has moved from the "cautious" zone (LSR < FB < USR) into the "healthy" zone (USR < FB, Figure 71) , however, there is considerable uncertainty in this biomass estimate as the westernmost portion of the survey stations in 4X were not completed. In addition, recruitment into next season is uncertain leading to the recommendation of a continued conservative harvest strategy pending further analysis prior to the 2015-2016 season.

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REFERENCES

Bailey, R. 1982. Relationship between catches of snow crab, *C. Opilio* (O. Fabricius) and abundance of cod *Gadus morhua* L. in the southwestern Gulf of St. Lawrence. Proceeding of the International Symposium on the Genus Chionoecetes, Alaska Sea Grant Report. 82-10:486–497.

Biron, M., Moriyasu, M., Wade, E., DeGrace, P., Campbell, R., and Hebert, M. 1997. Assessment of the 1996 snow crab (*Chionoecetes opilio*) fishery off eastern Cape Breton, Nova Scotia (CFAs 20 to 24, and 4X). Fisheries and Oceans Canada. Canadian Stock Assessment Secretariat. Research Document. 1997/102.

Biron, M., Wade, E., Moriyasu, M., DeGrace, P., Campbell, R., and Hebert, M. 1999. Assessment of the 1998 snow crab (*Chionoecetes opilio*) fisheries off eastern Nova Scotia (Areas 20 to 24, (and 4X)), Canada. Fisheries and Oceans Canada. Canadian Stock Assessment Secretariat. Research Document. 1999/12.

Boudreau, M., Courtenay, S.C., and Lee, K. 2009. Proceedings of a Workshop Held 23 January 2007 at the Gulf Fisheries Centre; Potential Impacts of Seismic Energy on Snow Crab: An Update to the September 2004 Review. Canadian Technical Report on Fisheries and Aquatic Sciences. 2836: vii+31 p.

Breeze, H., and Horsman, T. (Editors). 2005. The Scotian Shelf: An atlas of human activities. DFO/2005- 816.

Brodziak, J., and Link, J. 2002. Ecosystem management: What is it and how can we do it? Bulletin of Marine Science. 70:589-611.

Bundy, A. 2004. Mass balance models of the eastern Scotian Shelf before and after the cod collapse and other ecosystem changes. Canadian Technical Report on Fisheries and Aquatic Sciences. 2520.

Choi, J.S., and Patten, B.C. 2001. Sustainable development: Lessons from the paradox of enrichment. Journal of Ecosystem Health. 7:163-177.

Choi, J.S., and Zisserson, B.M. 2012. Assessment of Scotian Shelf snow crab in 2010. Fisheries and Oceans Canada. Canadian Science Advisory Secretariat. Research Document. 2011/110.

Choi, J.S., Frank, K.T., Petrie, B., and Leggett, W.C. 2005a. Integrated assessment of a large marine ecosystem: A case study of the devolution of the eastern Scotian Shelf, Canada. Oceanography and Marine Biology: An Annual Review. 43:47–67.

Choi, J., Zisserson, B., and Reeves, A. 2005b. An assessment of the 2004 snow crab populations resident on the Scotian Shelf (CFAs 20 to 24). Fisheries and Oceans Canada. Canadian Science Advisory Secretariat. Research Document. 2005/028.

CNSOPB (Canada-Nova Scotia Offshore Petroleum Board). 2015. Lands management: Call for bids forecast areas (2015–2017): Call for Bids Forecast Areas (2015-2017).

Comeau, M., Conan, G.Y., Maynou, F., Robichaud, G., Therriault, J.C., and Starr, M. 1998. Growth, spatial distribution, and abundance of benthic stages of the snow crab, *Chionoecetes opilio*, in Bonne Bay, Newfoundland, Canada. Canadian Journal of Fisheries and Aquatic Sciences. 55:262–279.

Conan, G.Y., Comeau, M., and Robichaud, G. 1992. Life history and fishery management of Majid crabs: The case study of the Bonne bay (Newfoundland) *Chionoectes opilio* population. International Council for the Exploration of the Seas. Council Meeting Document. 1992/K:21–21.

Cook, A.M., and Bundy, A. 2010. The food habits database: An update, determination of sampling adequacy, and estimation of diet for key species. Canadian Technical Report of Fisheries and Aquatic Sciences. 2884.

Courtenay, S.C., Boudreau,M. and Lee, K. (Editors). 2009. Potential Impacts of Seismic Energy on Snow Crab: An Update to the September 2004 Peer Review. Environmental Studies Research Funds Report No. 178. Moncton, 181 p.

Cressie, N. 1993. Statistics for spatial data. Wiley-Interscience, New York, NY. 900p.

DFO. 2004. Potential Impacts of Seismic Energy on Snow Crab. Fisheries and Oceans Canada. Canadian Science Advisory Report. Habitat Status Report. 2004/003.

DFO. 2005. Conference on the Governance of High Seas Fisheries and the United Nations Fish Agreement—Moving from Words to Action, St. John's, Newfoundland and Labrador; May 1-5, 2005. (Accessed 03 September 2015).

DFO. 2006. A harvest strategy compliant with the precautionary approach. Fisheries and Oceans Canada. Canadian Science Advisory Secretariat. Science Advisory Report 2006/023.

DFO. 2012. Assessment of Northern shrimp on the eastern Scotian Shelf (SFAs 13-15). Fisheries and Oceans Canada. Canadian Science Advisory Secretariat. Science Advisory Report. 2012/001.

DFO. 2014. Maritimes research vessel survey trends on the Scotian Shelf and Bay of Fundy. Fisheries and Oceans Canada. Canadian Science Advisory Secretariat. Science Response. 2014/017.

Diamond, J.M. 2005. Collapse: How societies choose to fail or succeed. Penguin, New York, NY. 608p.

Dawe, E., Mullowney, D., Colbourne, E., Han, G., Morado, J.F., and Cawthorn, R. 2010. Relationship of oceanographic variability with distribution and prevalence of bitter crab syndrome in snow crab (*Chionoecetes opilio*) on the Newfoundland–Labrador shelf. In Biology and management of exploited crab populations under climate change. Alaska Sea Grant, University of Alaska, Fairbanks, Alaska. doi:10.4027/bmecpcc.2010.06. pp.175-197.

Elner, R.W., and Beninger, P. 1995. Multiple reproductive strategies in snow crab, *Chionoecetes opilio*: Physiological pathways and behavioural plasticity. Journal of Experimental Marine Biology and Ecology. 193:93–112.

Emera. 2013. Newfoundland and Labrador Maritime link environmental assessment report. NSP Maritime Link Inc., Emera Newfoundland and Labrador Holdings Inc., St. John's, NL.

Evenden, G.I. 1995. Cartographic projection procedures for the UNIX environment–A user's manual. Manual for PROJ 4.4.9. (Accessed 03 September 2015).

FAO (Food and Agriculture Organization). 1995. FAO code of conduct for responsible fisheries. Food and Agriculture Organization of the United Nations, Rome, Italy. ISBN 92-5-103834-5.

Foyle, T., O'Dor, R., and Elner, R. 1989. Energetically defining the thermal limits of the snow crab. Journal of Experimental Biology. 145:371–393.

Gelman, A., and Hill, J. 2007. Data analysis using regression and multilevel/hierarchical models. Cambridge University Press, New York, NY. 625p.

Hooper, R. 1986. A spring breeding migration of the snow crab, *Chionoectes opilio* (O. Fabr.), into shallow water in Newfoundland. Crustaceana. 50:257–264.

Hunt Oil. 2005. CNSOPB Program # NS24-H33-1P. Hunt Oil Company of Canada, Inc. 2D Seismic. Contractor Geophysical Services Incorporated. Vessel M/V *Gulf Pacific*. Start Date 03-Nov-05. Total # Km's Acquired/ Projected 920.53 km / 940.25 km. Report Date 23-Nov-05 (program completed 20-November-2005).

Katona, S. and Whitehead, H. 1988. Are cetacea ecologically important? Oceanography and Marine Biology Annual Reviews. 26: 553-568.

Koeller, P., Savard, L., Parsons, D., and Fu, C. 2000. A precautionary approach to assessment and management of shrimp stocks in the Northwest Atlantic. Journal of Northwest Atlantic Fisheries Science. 27:235-247.

Koeller, P., Covey, M., and King, M. 2006. An assessment of the eastern Scotian Shelf shrimp stock and fishery for 2005 and outlook for 2006. Fisheries and Oceans Canada. Canadian Science Advisory Secretariat. Research Document. 2006/001.

Kuhn, P., and Choi, J.S. 2011. Influence of temperature on embryo developmental cycles and mortality of female *Chionoecetes opilio* (snow crab) on the Scotian Shelf, Canada. Fisheries Research. 107:245-252.

Laurans, M., and Smith. M.T. 2007. Bayesian production model assessment of edible crab in the English Channel. International Council for the Exploration of the Seas. Council Meeting Document. 2007/O:29.

Lilly, G. 1984. Predation by Atlantic cod on shrimp and crab off north-eastern Newfoundland in autumn of 1977-82. International Council for the Exploration of the Seas. Council Meeting Document. 1984/G:53.

Morado, J.F., Dawe, E., Mullowney, D., Shavey, C., Lowe, V., Cawthorn, R. 2010. Climate change and the worldwide emergence of Hematodinium-associated disease: Is there evidence for a relationship? In Biology and management of exploited crab populations under climate change. Alaska Sea Grant, University of Alaska, Fairbanks, Alaska. doi:10.4027/bmecpcc.2010.08. pp. 153-173.

Paine, R.T. 1966. Food web complexity and species diversity. The American Naturalist. 100:65–75.

Plummer, M. 2003. JAGS: A program for analysis of Bayesian graphical models using Gibbs sampling. In Proceedings of the 3rd International Workshop on Distributed Statistical Computing (DSC 2003). Edited by K. Hornik, F. Leisch, and A. Zeileis. Technische Universitat Wien, Vienna, Austria. ISSN 1609-395X. 10 pp. (Accessed 03 September 2015).

Plummer, M. 2008. Penalized loss functions for Bayesian model comparison. Biostatistics. 9:523-539.

Plummer, M. 2010. Just Another Gibbs Sampler (JAGS). Version 2.20 manual. International Agency for Research on Cancer. Lyon, France. (Accessed 21 September 2015).

Pubela, O., Sevigny, J-M., Saint-Marie, B., Crethes, J-C. Burmeister, A. Dawe, E.G. and Moriyasu, M. 2008. Population genetic structure of the snow crab (*Chionoecetes opilio*) at the Northwest Atlantic scale. Canadian Journal of Fisheries and Aquatic Sciences. 65: 425-436.

R Development Core Team. 2012. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing. Vienna, Austria. ISBN 3-900051-07-0. (Accessed 03 Septmeber 2015).

Robichaud, D.A., Bailey, R.F.J., and Elner, R.W. 1989. Growth and distribution of snow crab, *Chionoecetes opilio*, in the southeastern Gulf of St. Lawrence. Journal of Shellfish Research. 8:13–23.

Robichaud, D.A., Elner, R.W., and Bailey, R.F.J. 1991. Differential selection of crab *Chionoecetes opilio* and *Hyas* spp. as prey by sympatric cod *Gadus morhua* and thorny skate *Raja radiata*. Fishery Bulletin. 89:669–680.

Sainte-Marie, B. 1993. Reproductive cycle and fecundity of primiparous and multiparous female snow crab, *Chionoecetes opilio*, in the northwest Gulf of Saint Lawrence. Canadian Journal of Fisheries and Aquatic Sciences. 50:2147–2156.

Sainte-Marie, B., and Hazel, F. 1992. Molting and mating of snow crabs, *Chionoecetes opilio*, in shallow waters of the northwest Gulf of St. Lawrence. Canadian Journal of Fisheries and Aquatic Sciences. 49:1282–1293.

Sainte-Marie, B., and Lafrance, M. 2002. Growth and survival of recently settled snow crab *Chionoecetes opilio* in relation to intra- and intercohort competition and cannibalism: A laboratory study. Marine Ecology Progress Series. 244:191–203.

Sainte-Marie, B., Raymond, S., and Brethes, J.-C. 1995. Growth and maturation of the benthic stages of male snow crab, *Chionoecetes opilio* (Brachyura: Majidae). Canadian Journal of Fisheries and Aquatic Sciences. 52:903–924.

Shelton, P.A., and Sinclair, A.F. 2008. It's time to sharpen our definition of sustainable fisheries management. Canadian Journal of Fisheries and Aquatic Sciences. 65:2305–2314.

Smith, S.J. 1997. Bootstrap confidence limits for groundfish survey trawl estimates of mean abundance. Canadian Journal of Fisheries and Aquatic Sciences. 54(3): 616-630.

Squires, H.J., and Dawe, E.G. 2003. Stomach contents of snow crab (*Chionoecetes opilio)*, Decapoda, Brachyura from the Northeast Newfoundland Shelf. Journal of Northwest Atlantic Fisheries Science. 32:27–38.

Stentiford, G.D., and Shields, J.D. 2005. A review of the parasitic dinoflagellates Hematodinium species and Hematodinium-like infections in marine crustaceans. Diseases of Aquatic Organisms. 66:47–70.

Taylor, D.M., and Khan, R.A. 1995. Observations on the occurrence of Hematodinium sp. (Dinoflagellata: Syndinidae), the causative agent of bitter crab disease in Newfoundland snow crab (*Chionoecetes opilio*). Journal of Invertebrate Pathology. 65:283–288.

UNCHE (United Nations Conference on the Human Environment). 1972. Report of the United Nations Conference on the Human Environment in Stockholm. United Nations Environment Programme. (Accessed 03 September 2015).

UNCED (United Nations Conference on Environment and Development). 1992. Agenda 21, the Rio Declaration on Environment and Development, the Statement of Forest Principles, the United Nations Framework Convention on Climate Change and the United Nations Convention on Biological Diversity; Rio de Janeiro, 3-14 June 1992. A/CONF.151/26 (Vol. I).

UNCLOS (United Nations Convention on the Law of the Sea). 1982. Agreement relating to the implementation of Part XI of the Convention. Division for Oceans Affairs and the Law of the Sea, Office of Legal Affairs, United Nations. (Accessed 03 September 2015).

UNFA (United Nations Fish Stocks Agreement). 2001. The United Nations Agreement for the implementation of the provisions of the united nations convention on the law of the sea of December 10, 1982 relating to the conservation and management of straddling fish stocks and highly migratory fish stocks (in force as of from 11 December 2011). Division for Oceans Affairs and the Law of the Sea, Office of Legal Affairs, United Nations. A/CONF.164/37. (Accessed 03 September 2015).

WCED (World Commission on Environment and Development). 1987. Our common future, Report of the World Commission on Environment and Development. Development and International Co-operation: Environment. General Assembly Document A/42/427. (Accessed 03 September 2015).

WSSD (World Summit on Sustainable Development). 2002. Report of the World Summit on Sustainable Development. Johannesburg, South Africa; 26 August - 4 September 2002. A/CONF. 199/20. (Accessed 29 September 2015).

Wade, E., Surette, T., Apaloo, J. and Moriyasu, M. 2003. Estimation of mean annual natural mortality for adult male snow crab *Chionoecetes opilio* in the southern Gulf of St. Lawrence. Fisheries and Oceans Canada. Canadian Science Advisory Secretariat. Research Document. 2003/017.

Webb, J.B., Eckert G.L., Shirley, T.C., and Tamone, S.L. 2007. Changes in embryonic development and hatching in *Chionecetes opilio* (Snow Crab) with variation in incubation temperature. Biological Bulletin. 213:67-75.

Watson, J. 1972. Mating behaviour of the spider crab, *Chionoecetes opilio*. Journal of the Fisheries Research Board of Canada. 29:447–449.

Wessel, P., and Smith, W.H.F. 1998. New, improved version of generic mapping tools released. EOS Transactions of the American Geophysical Union. 79:579–593.

Wood, S. 2006. Generalized additive models: An introduction with R. CRC Texts in Statistical Science Series. Volume 67. Chapman and Hall/CRC, Boca Raton, FL.

Worm, B., and Myers, R. 2003. Meta-analysis of cod-shrimp interactions reveals top-down control in oceanic food webs. Ecology. 84:162–173.

TABLES

Table 1: Snow crab fishing seasons on the Scotian Shelf in the year 2013.

Area	Season
N-ENS	Apr 13 – May 13 & July 13- Aug 23
S-ENS (CFA 23)	Apr 2 – Sept 1
S-ENS (CFA 24)	Apr 2 – Sept 30
4X	Nov 1 (2012) – March 31 (2013), *Extended to April 30 due to low landings*

Table 2: Summary of snow crab fisheries activity of N-ENS.

Year	Licenses	TAC (t)	Landings (t)	CPUE (kg/trap haul)	Effort (x1000 trap hauls)
1999	78	900	899	55	16.4
2000	79	1,015	1,017	68	14.9
2001	80	1,065	1,066	94	11.3
2002	80	1,493	1,495	101	14.8
2003	80	1,493	1,492	77	19.4
2004	79	1,416	1,418	61	23.4
2005	78	566	562	31	18.4
2006	78	487	486	36	13.7
2007	78	244	233	24	9.9
2008	78	244	238	34	7.0
2009	78	576	579	76	7.6
2010	78	576	576	55	10.5
2011	78	534	536	110	4.8
2012	78	603	603	117	5.1
2013	78	783	783	106	7.4
2014	78	783	778	104	7.4

Table 3: Summary of snow crab fisheries activity of S-ENS. Dash (-) in the licenses column represents the year where alterations in number of licenses occurred with the Marshall Decision.

Year	Licenses	TAC (t)	Landings (t)	CPUE (kg/trap haul)	Effort (x1000 trap hauls)
1999	-	2,700	2,700	71	38.0
2000	158	8,799	8,701	85	102.4
2001	163	9,023	9,048	88	103.1
2002	149	9,022	8,891	112	79.6
2003	145	9,113	8,836	99	89.6
2004	130	8,241	8,022	106	76.0
2005	114	6,353	6,407	110	58.5
2006	114	4,510	4,486	91	49.4
2007	115	4,950	4,942	100	49.3
2008	115	8,316	8,253	96	85.9
2009	116	10,800	10,645	90	118.8
2010	116	13,200	13,150	103	128.3
2011	116	12,120	12,135	106	118.8
2012	116	11,707	11,733	98	120
2013	116	11,311	11,309	104	108.7
2014	116	11,311	11,267	112	100.2

Table 4: Summary of snow crab fisheries activity of 4X. Data prior to 2002/03 (dashes) was not available.

Year	Licenses	TAC (t)	Landings (t)	CPUE (kg/trap haul)	Effort (x1000 trap hauls)
1998/09	4	-	70	-	-
1999/00	4	-	119	-	-
2000/01	6	-	213	-	-
2001/02	8	520	376	-	-
2002/03	9	600	221	10	21.9
2003/04	9	600	289	13	22.8
2004/05	9	600	413	20	20.8
2005/06	9	337.6	306	29	10.8
2006/07	9	337.6	317	28	11.5
2007/08	9	230	220	18	12.1
2008/09	9	230	229	28	8.0
2009/10	9	230	229	36	6.4
2010/11	9	346	345	38	9.0
2011/12	9	346	344	29	11.8
2012/13	9	263	118	13	9.6
2013/14	9	80	79	15	5.1
2014/15[1]	9	80	59	34	1.7

Note: [1]As of February 10, 2015. Season still in progress.

Table 5: Snow crab carapace conditions (CC) and their description. Hardness is measured by a durometer.

Carapace Condition (CC)	Category	Hardness	Description	Age after terminal molt (approximate)
1	New soft	< 68	claws easily bent, carapace soft, brightly coloured, iridescent, no epibionts	0 - 5 months
2	Clean	variable	claws easily bent, carapace soft, brightly coloured, iridescent, some epibionts	5 months – 1 year
3	Intermediate	> 68	carapace hard, dull brown dorsally, yellow-brown ventrally, no iridescence, shell abrasion, epibionts	8 months – 3 years
4	Old	> 68	carapace hard, very dirty, some decay at leg joints, some epibionts	2 - 5 years
5	Very old	variable	carapace soft, very dirty, extensive decay, extensive epibionts	4 - 6 years

Table 6: Tagging effort by year since 2008. Rows represent results of all tagged crab within a single year. Average and maximum displacement represents the mean and maximum of the shortest path distance between marking and recapture locations. – represents no data for the metric.

Year	Tags Applied	Tags Returned	Distinct Tags Returned	Avg. Displacement (km)	Max Displacement (km)	Avg. Days to Capture	Max Days to Capture	Avg. km/ month
2008	979	60	58	20.57	184.26	280	1736	2.23
2009	195	14	13	14.78	52.26	338	734	1.43
2010	2256	160	148	36.00	151.71	429	1124	2.59
2011	1789	103	102	58.47	261.50	486	1203	3.64
2012	1676	196	159	22.21	211	246	830	2.69
2013	3966	181	175	39.39	187.47	306	456	3.91
2014	3112	23	21	6.82	27.05	35	82	–
All Years/ Areas	18225	1164	1086	28.06	308.65	342	1736	2.49

Table 7: Statistics of the tagging effort and results separated by crab fishing area combining all years of data.

Area	Tags Applied	Distinct Tags Returned	Avg. Displacement (km)	Avg. Days to Capture	Avg. km/month	Number of Fishermen Returning Tags
S-ENS	10951	624	25.21	362	2.12	76
N-ENS	6759	411	39.87	371	3.26	56
4X	515	84	7.78	137	1.7	13

Table 8: Predators of snow crab in ENS during the 1995-2009 time period. In each period, N stomachs represents the number of stomachs examined, Freq (%) is the percent of stomachs containing snow crab as prey, and Weight (%) is the percent of total weight represented by snow crab as prey.

Predator Species	N Stomachs	Freq (%)	Weight (%)
Atlantic cod	6059	0.31	0.18
Haddock	4059	0.05	0.01
White hake	2523	0.08	0.01
Atlantic halibut	556	1.44	1.35
American plaice	7694	0.05	0.05
Atlantic wolfish	519	1.35	1.62
Thorny skate	2528	0.24	0.73
Smooth skate	502	1.00	2.14
Winter skate	547	0.18	0.11
Longhorn sculpin	1888	0.32	0.34
Sea raven	611	0.33	0.57

Table 9: Prevalence of bitter crab disease (BCD) on the Scotian Shelf. Total crab refers to the number of crab examined, Visible BCD crab represents those suggested to be positive. Infection rate is the proportion of positives and %male is the proportion of crab with BCD that are male.

Survey Year	Total Crab	Visible BCD (+) Crab	Infection Rate	% Male (BCD +)
2008	31,315	24	0.077%	54%
2009	29,168	33	0.113%	61%
2010	31,197	19	0.061%	53%
2011	24,852	22	0.089%	59%
2012	20,355	16	0.079%	62%
2013	21,715	16	0.074%	56%
2014	23,512	20	0.085%	54%

Table 10: Bycatch (kg) estimates of finfish and invertebrates from the ENS snow crab fishery. The estimates are extrapolated from at-sea-observed bycatch and at-sea-observed biomass of catch [i.e., estimated biomass of bycatch = observed biomass of bycatch species / (observed landings of snow crab / total landings of snow crab)]. The snow crab fishery is very species-specific as bycatch levels are approximately 0.011% of snow crab landings for the past three years in ENS.

Species	2012	2013	2014	3-Year Total
Witch Flounder	0	67	0	67
Northern Stone Crab	45	90	0	135
Redfish	89	112	0	201
Sea Cucumber	668	112	0	780
Spotted Wolffish	189	495	0	684
Striped Wolffish	33	382	0	415
Northern Wolffish	22	0	0	22
Toad Crab	367	22	0	389
Atlantic Cod	724	0	22	746
Jonah Crab	11	0	0	11
Eelpout	22	0	0	22
Sculpin	11	67	0	78
Ocean Pout	22	0	0	22
Seals (NS)	334	0	0	334
Sea Raven	0	90	0	90
Skate (NS)	22	0	0	22
Shrimp (NS)	0	22	0	22
Snow Crab Landings	**12,310,000**	**12,093,000**	**12,046,000**	**36449000**

Table 11: Bycatch (kg) estimates from the 4X snow crab fishery. The estimates are extrapolated from at-sea-observed bycatch and at-sea-observer coverage, by biomass [i.e., estimated biomass of bycatch = observed biomass of bycatch species / (observed landings of snow crab / total landings of snow crab)]. Bycatch levels have been at 0.92% of total landings in the past three years. The 2013 and 2014 fishery showed a substantial increase in bycatch levels as snow crab catch rates were very low and the spatial extent of the fishery expanded to attempt to locate crab.

Species	2012	2013	2014	3-Year Total
Jonah Crab	16	0	94	110
Northern Stone Crab	540	1782	594	2916
Deepsea Red Crab	33	318	539	890
American Lobster	0	188	438	626
Lumpfish	0	0	8	8
Redfish	0	14	0	14
Cod	0	43	0	43
Longhorn Sculpin	0	14	0	14
Sea Raven	0	246	109	355
Snow Crab Landings	**344,687**	**117,827**	**79,000**	**541,514**

Table 12: Carapace condition (CC) of crab ≥ 95 mm CW (percent by number) over time for N-ENS from at-sea-observed data.

Year	CC1	CC2	CC3	CC4	CC5
2004	1.63	5.23	72.36	20.33	0.44
2005	5.48	8.65	65.88	19.11	0.89
2006	3.87	9.68	71.14	13.67	1.64
2007	44.53	11.17	36.26	7.22	0.82
2008	26.84	4.21	61.33	6.86	0.75
2009	0.23	3.3	92.11	4.35	0.02
2010	1.6	1.56	92.61	3.97	0.25
2011	0	2.6	94.3	3	0.1
2012	0	2.9	95.4	1.7	0
2013	0	5.9	75.5	17.2	1.4
2014	0.1	18.6	72.1	8.9	0.3

Table 13: Carapace condition (CC) of crab ≥ 95 mm CW (percent by number) over time for S-ENS from at-sea-observed data.

Year	CC1	CC2	CC3	CC4	CC5
2004	2.29	4.18	74.56	18.19	0.78
2005	4.94	11.42	68.48	14.42	0.74
2006	6.16	17.85	68.45	7.24	0.3
2007	7.95	15.61	58.48	16.32	1.63
2008	10.12	8.57	67.93	12.34	1.03
2009	8.34	7.43	64.73	16.97	2.53
2010	2.5	9.75	79.53	7.25	0.96
2011	0.57	9.5	85.0	4.8	0.1
2012	0.29	10.16	85.28	4.2	0.07
2013	0.21	3.31	93.60	2.8	0
2014	1.2	15.9	78.1	4.6	0.1

Table 14: Carapace condition (CC) of crab ≥ 95 mm CW (percent by number) over time for 4X from at-sea-observed data.

Year	CC1	CC2	CC3	CC4	CC5
2004/05	0.05	1.97	93.56	4.36	0.05
2005/06	0	11.79	84.96	3.22	0.04
2006/07	0.05	0.5	98.01	1.44	0
2007/08	0.18	0.09	78.75	20.75	0.23
2008/09	0.32	0.16	56.98	42.47	0.08
2009/10	0.04	0.5	98.89	0.57	0
2010/11	0.25	1.23	54.28	44.17	0.07
2011/12	0.05	0.5	91.1	8.1	0.2
2012/13	0	1	82.9	15.1	1
2013/14	0	3.2	80.9	15.6	0.2

Table 15: Carapace condition (CC) of crab ≥ 95 mm CW (percent by number) over time for N-ENS from trawl surveys. The transition from a spring to a fall survey occurred in 2002/2003. Crude unadjusted proportions.

Year	CC1	CC2	CC3	CC4	CC5
2003	4.42	18.92	57.25	18.67	0.74
2004	0	4.48	51.74	39.3	4.48
2005	0	0	51.63	35.29	13.07
2006	0	18.52	15.74	42.59	23.15
2007	0	23.81	67.35	7.48	1.36
2008	0.14	41.77	50.88	7.21	0
2009	3.53	30.59	64	1.88	0
2010	0	39.05	56.67	4.17	0.12
2011	0.11	38.2	56.75	4.94	0
2012	0	16.89	73.91	9.2	0
2013	0.24	51.22	43.4	5.01	0.12
2014	0	13.5	79.6	6.8	0

Table 16: Carapace condition (CC) of crab ≥ 95 mm CW (percent by number) over time for S-ENS from trawl surveys. The transition from a spring to a fall survey occurred in 2002/2003. Crude unadjusted proportions.

Year	CC1	CC2	CC3	CC4	CC5
2003	26.92	8.59	50.36	12.46	1.67
2004	5.12	16.98	56.18	20.72	1
2005	0.68	19.96	62.92	15.72	0.72
2006	1.15	17.98	61.55	17.56	1.76
2007	1.37	57.88	31.29	8.89	0.57
2008	0.58	15.12	69.83	13.93	0.54
2009	0.17	25.09	66.45	8.01	0.28
2010	0.22	26.29	71.08	2.22	0.2
2011	0.03	18.87	78.32	2.68	0.1
2012	0.03	18.76	77.57	3.41	0.23
2013	0.09	28.24	65.94	5.54	0.19
2014	0.16	11.43	84.25	4.04	1.1

Table 17: Carapace condition (CC) of crab ≥ 95 mm CW (percent by number) over time for 4X from trawl surveys. The transition from a spring to a fall survey occurred in 2002/2003. Crude, unadjusted proportions.

Year	CC1	CC2	CC3	CC4	CC5
2005	0	4.4	93.41	2.2	0
2006	0	6.94	83.33	8.33	1.39
2007	0	15.79	78.95	5.26	0
2008	0	1.61	90.32	8.06	0
2009	1.06	10.05	83.6	5.29	0
2010	2.88	21.15	71.15	4.81	0
2011	0	11.11	85.19	3.7	0
2012	0	3.7	51.85	40.74	3.7
2013	7.69	15.38	69.23	7.69	0
2014	0	0	94.23	5.71	0

FIGURES

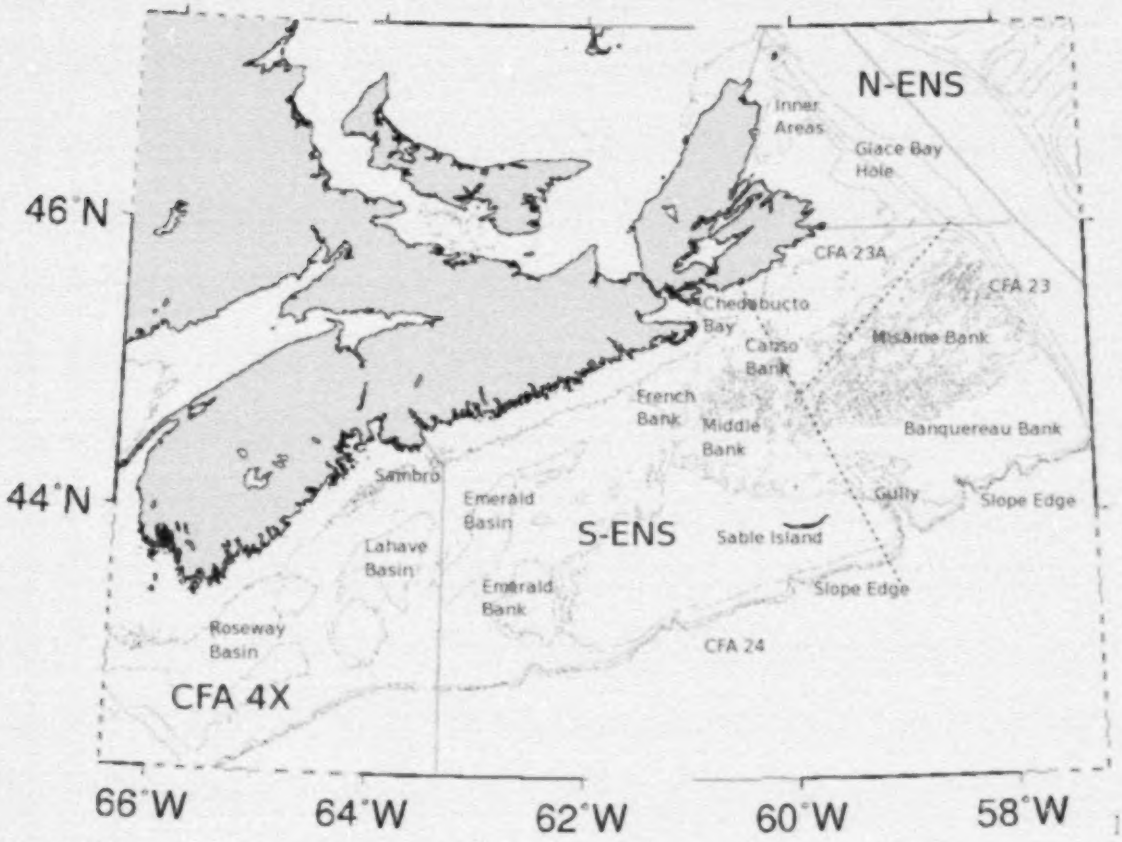


Figure 1: Map of geographic and management areas for snow crab on the Scotian Shelf.

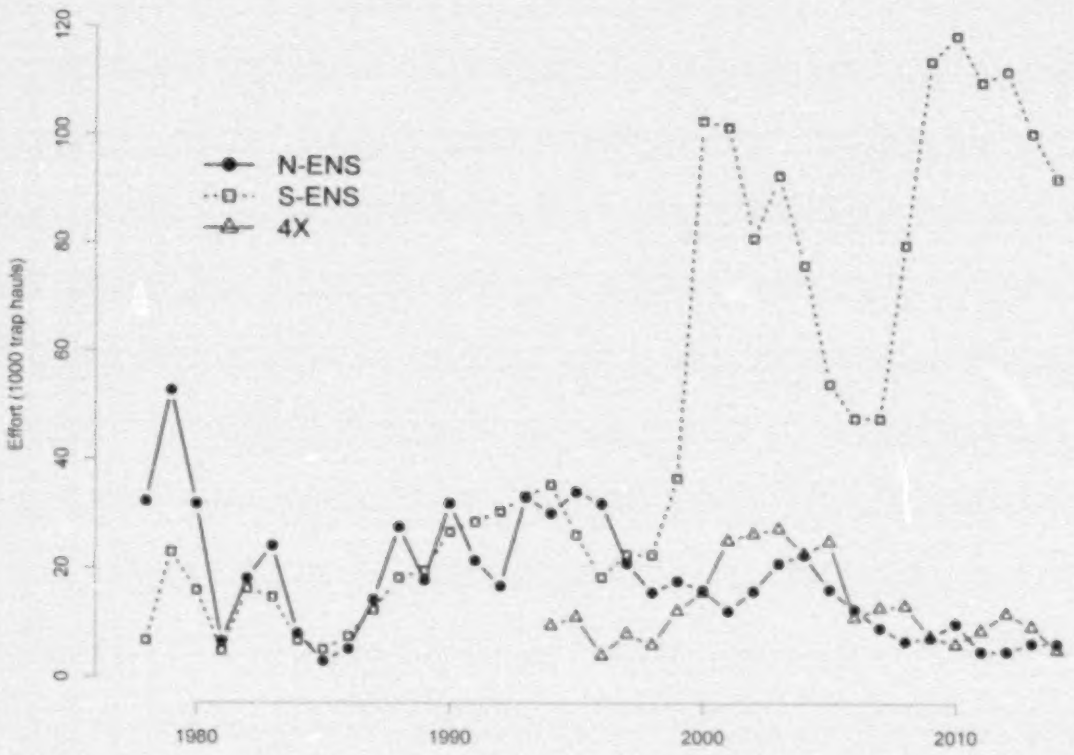


Figure 2: Temporal variations in the fishing effort for snow crab on the Scotian Shelf expressed as the number of trap hauls. Year in 4X refers to the start of the fishing season (from 1978 to 2014).

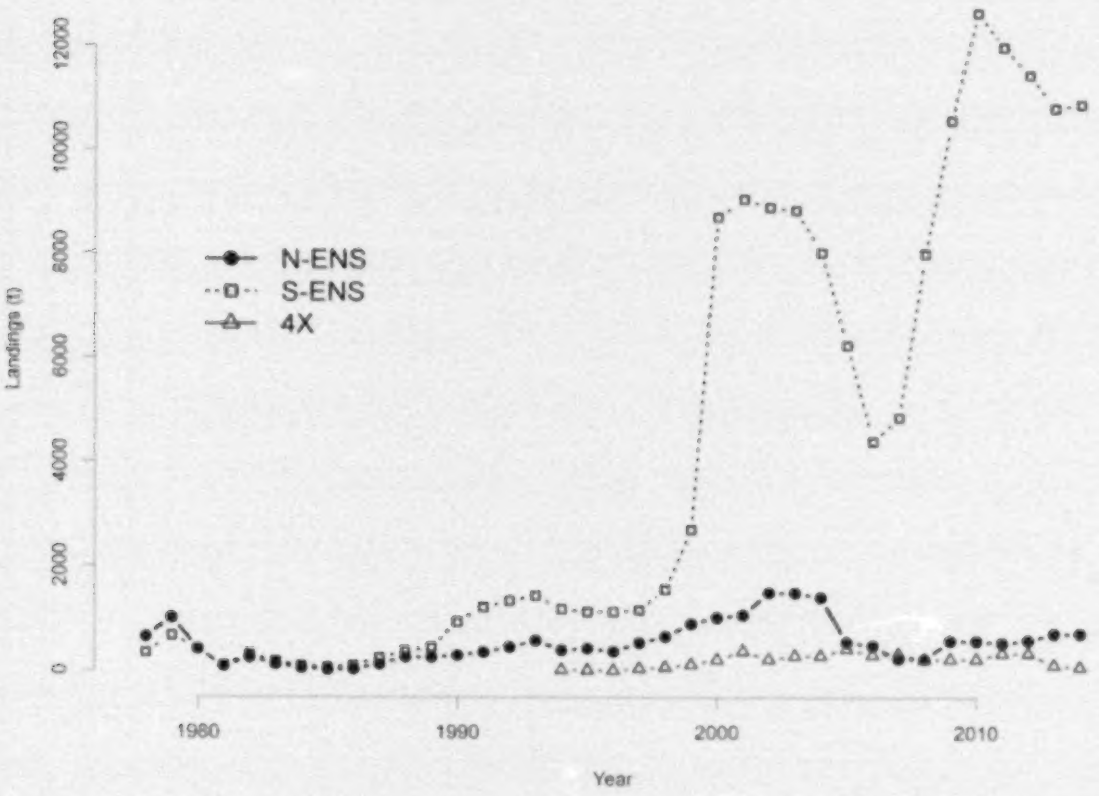


Figure 3: Temporal variations in the landings (t) for snow crab on the Scotian Shelf from 1978 to 2014. Year in 4X refers to the start of the fishing season. The landings follow TACs with very little variation.

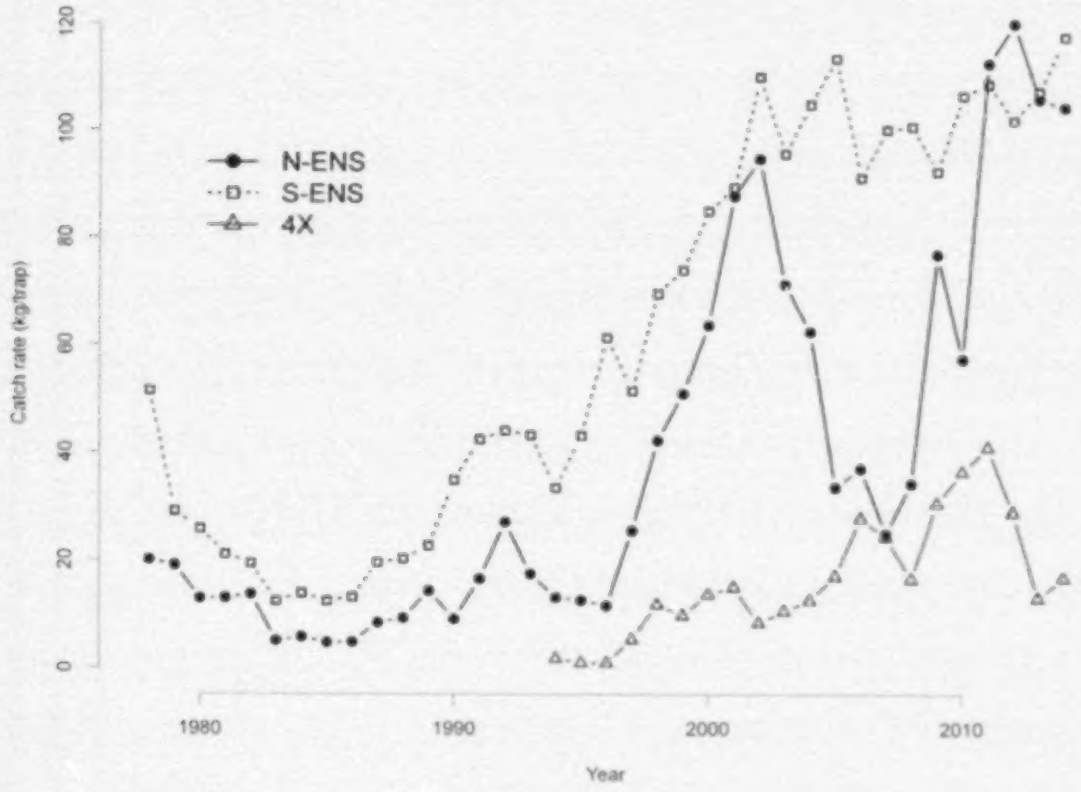
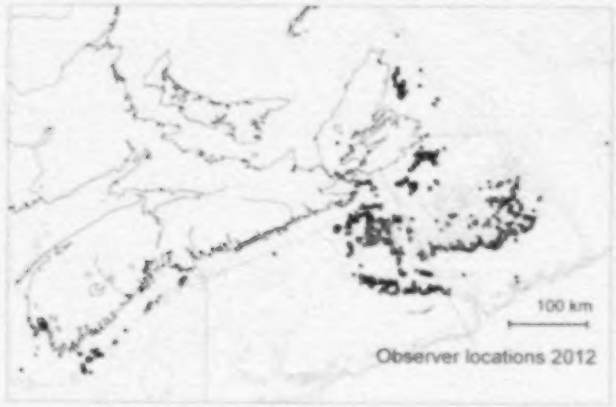


Figure 4: Temporal variations in the catch rates for snow crab on the Scotian Shelf from 1978 to 2014. Values are expressed as kilograms per trap haul, as obtained from logbook information. Year in 4X refers to the start of the fishing season. Trap design and size have changed over time. No corrections for varying trap types, soak times or bait types have been applied.



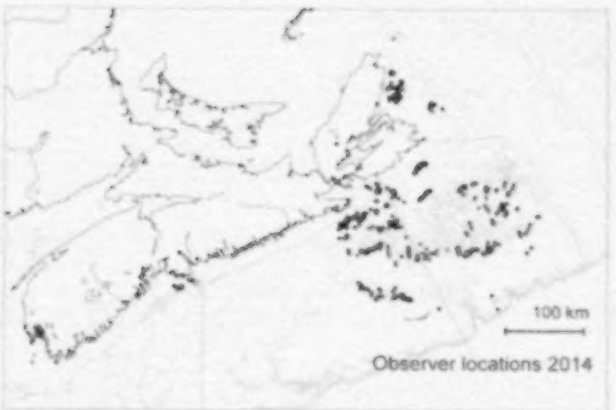


Figure 5: Locations of the observed snow crab fishing trips on the Scotian Shelf during each of the past three fishing seasons (2012, 2013, 2014).

Figure 6: Locations of snow crab survey trawl sets on the Scotian Shelf during each of the past three fishing seasons (2012, 2013, 2014).

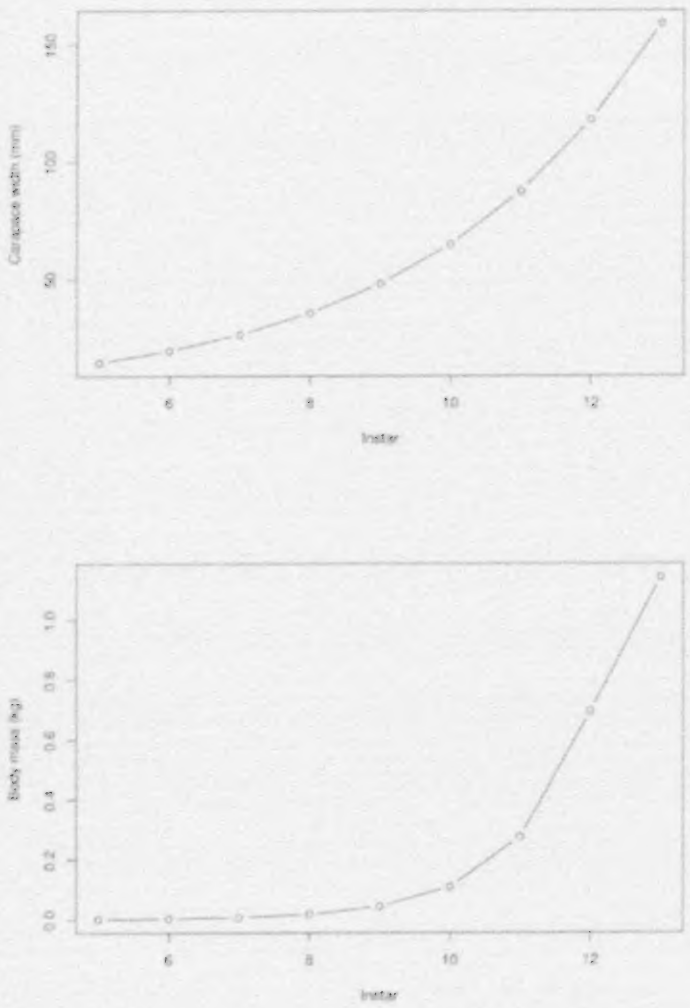


Figure 7: Growth in weight for each instar stage determined from modal length frequency analysis of male snow crab on the Scotian Shelf.

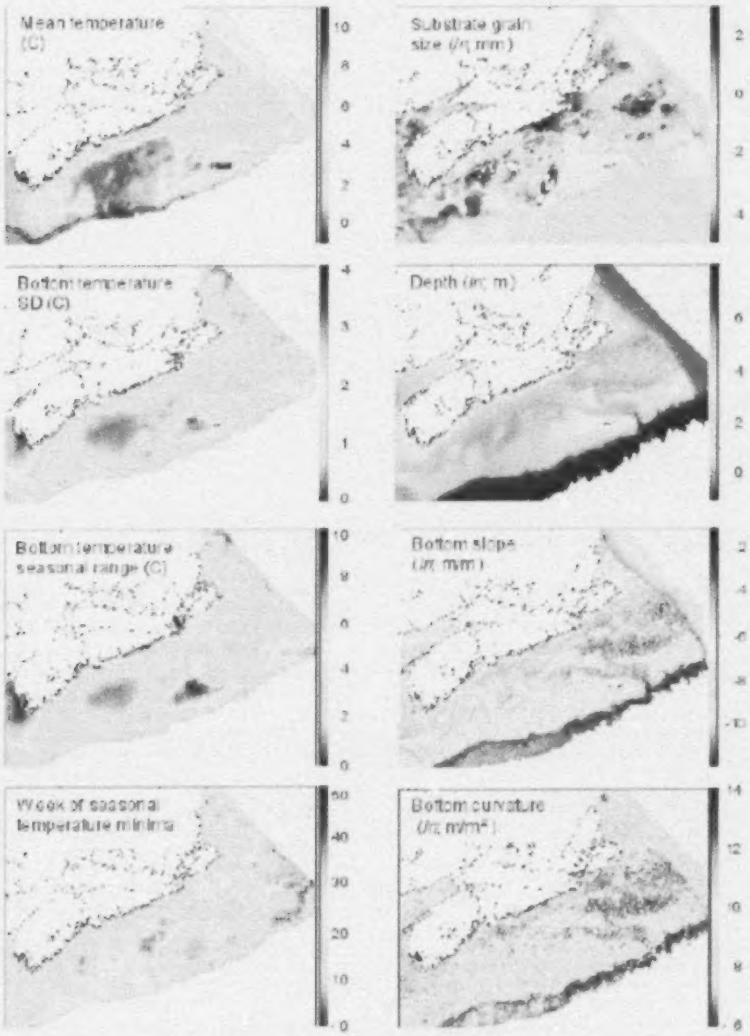

Mean temperature (C)
Substrate grain size (phi, mm)
Bottom temperature SD (C)
Depth (m, m)
Bottom temperature seasonal range (C)
Bottom slope (m, m/m)
Week of seasonal temperature minima
Bottom curvature (m, m/m²)

Figure 8: Ocean characteristics used for modeling snow crab habitat. The visualization of temperature variations are for climatological means. Annual temperature variations are used in modeling.

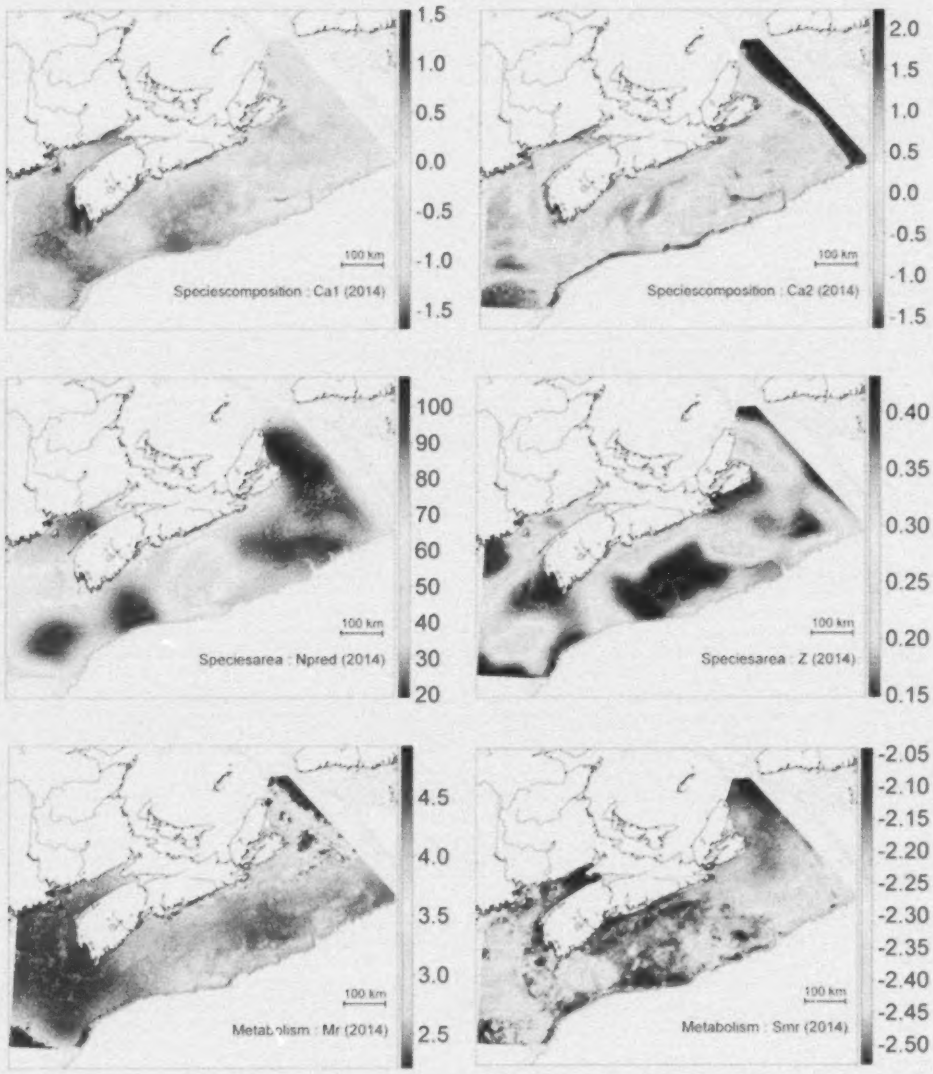


Figure 9: Community composition and ecological characteristics used in snow crab habitat modeling. Annual time series are used.

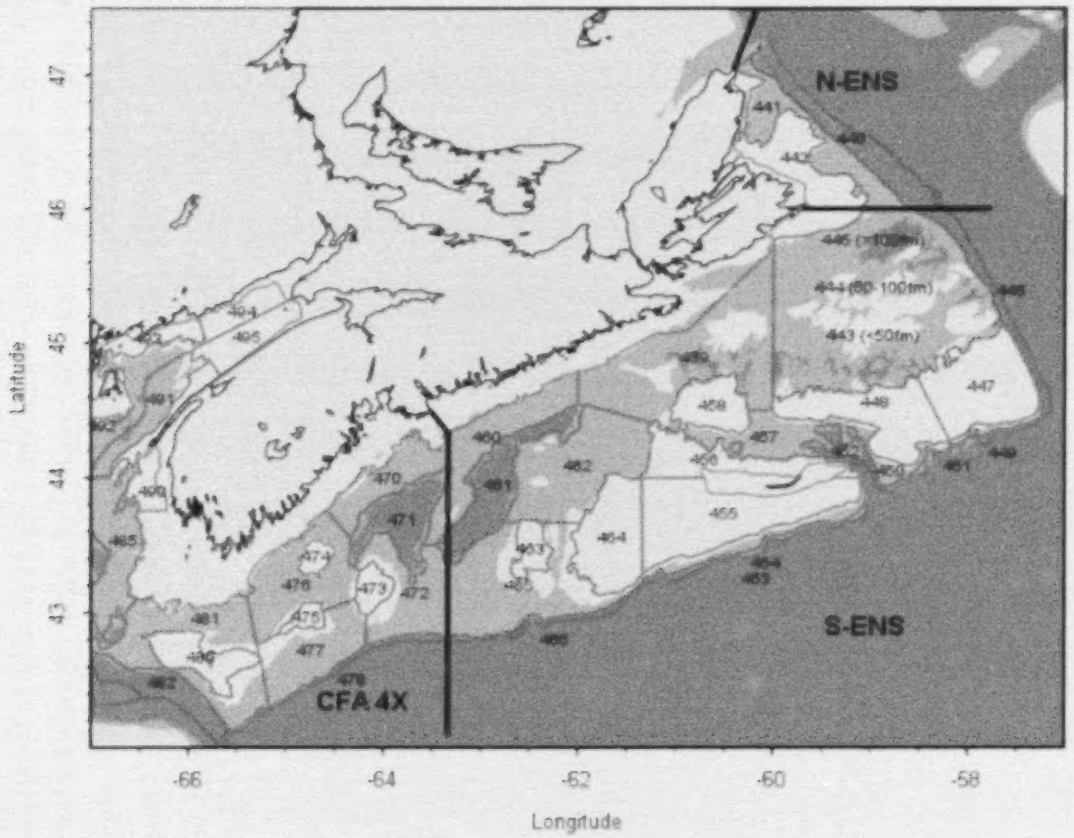


Figure 10: The summer DFO R/V groundfish survey strata overlain with the snow crab fishing areas. Trends in groundfish biomass indices for N-ENS were estimated using the data from strata 440-442, S-ENS 443-467 and 4X 470-483.

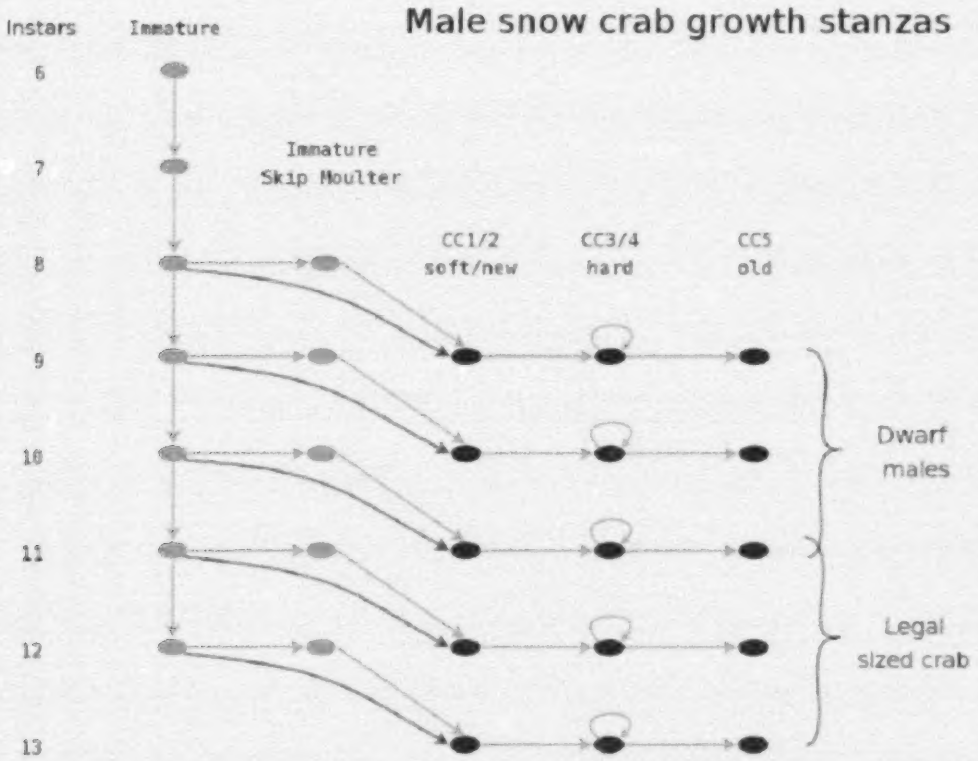


Figure 11: The growth stanzas of male snow crab. Each instar is determined from carapace width (CW) bounds obtained through modal analysis and categorized to carapace conditions (CC) and maturity from visual inspection and/or morphometric maturity equations. Snow crab are resident in each growth stanza for 1 year, with the exception of CC2 – CC4 which are known from mark recapture experiments to last between 3-5 years.

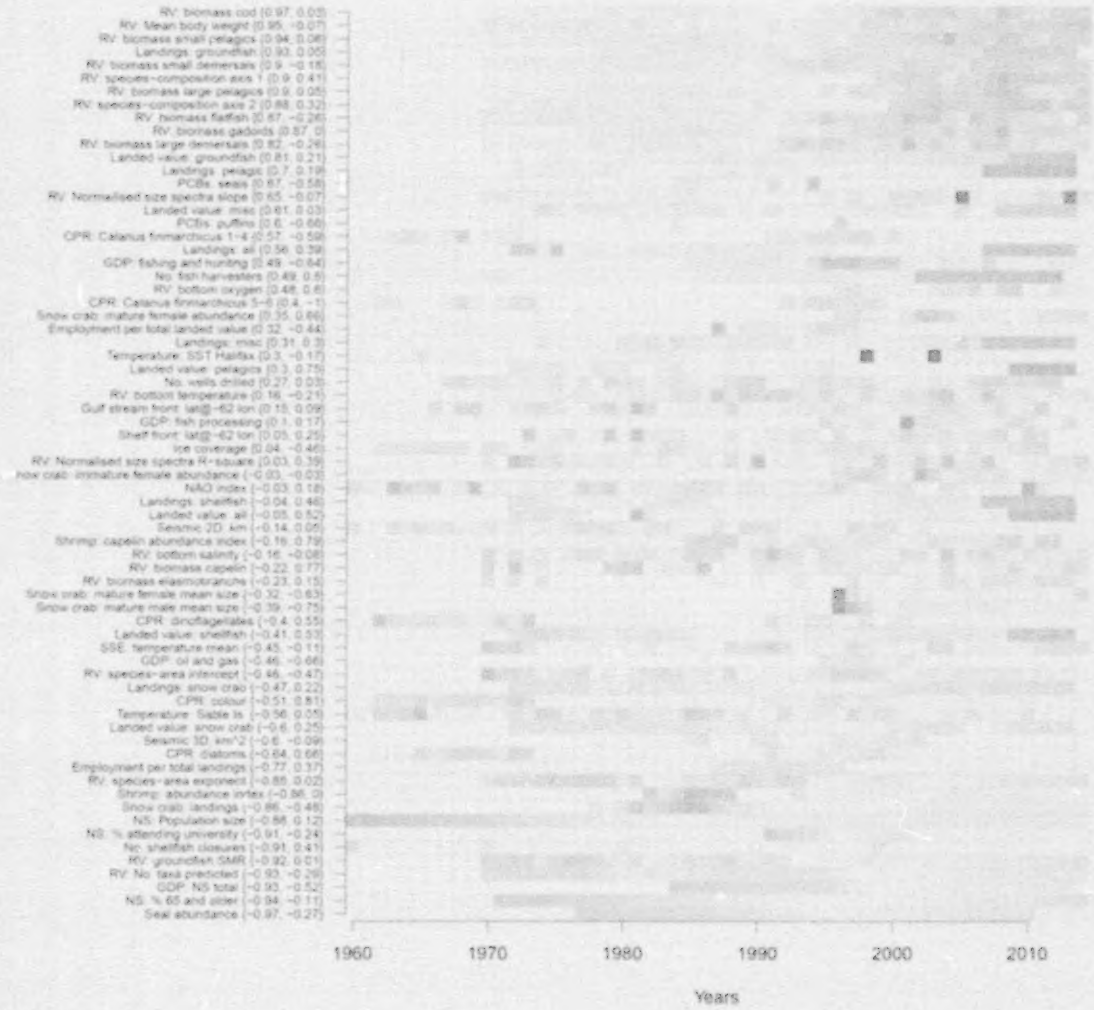

RV: biomass cod (0.97, 0.03)
RV: Mean body weight (0.95, -0.07)
RV: biomass small pelagics (0.94, 0.06)
Landings: groundfish (0.93, 0.05)
RV: biomass small demersals (0.9, -0.15)
RV: species-composition axis 1 (0.9, 0.41)
RV: biomass large pelagics (0.9, 0.05)
RV: species-composition axis 2 (0.88, 0.32)
RV: biomass flatfish (0.87, -0.26)
RV: biomass gadoids (0.87, 0)
RV: biomass large demersals (0.82, -0.24)
Landed value: groundfish (0.81, 0.21)
Landings: pelagic (0.7, 0.19)
PCBs: seals (0.67, -0.58)
RV: Normalised size spectra slope (0.65, -0.07)
Landed value: misc (0.61, 0.03)
PCBs: puffins (0.6, -0.66)
CPR: Calanus finmarchicus 1-4 (0.57, -0.59)
Landings: all (0.56, 0.39)
GDP: fishing and hunting (0.49, -0.64)
No. fish harvesters (0.49, 0.6)
RV: bottom oxygen (0.48, 0.6)
CPR: Calanus finmarchicus 5-6 (0.4, -1)
Snow crab: mature female abundance (0.35, 0.66)
Employment per total landed value (0.32, -0.44)
Landings: misc (0.31, 0.3)
Temperature: SST Halifax (0.3, -0.17)
Landed value: pelagics (0.3, 0.75)
No. wells drilled (0.27, 0.03)
RV: bottom temperature (0.16, -0.21)
Gulf stream front: lat@-62 lon (0.15, 0.09)
GDP: fish processing (0.1, 0.17)
Shelf front: lat@-62 lon (0.05, 0.25)
Ice coverage (0.04, -0.46)
RV: Normalised size spectra R-square (0.03, 0.39)
Snow crab: immature female abundance (-0.03, -0.03)
NAO index (-0.03, 0.18)
Landings: shellfish (-0.04, 0.46)
Landed value: all (-0.05, 0.52)
Seismic 2D: km (-0.14, 0.05)
Shrimp: capelin abundance index (-0.19, 0.79)
RV: bottom salinity (-0.19, -0.08)
RV: biomass capelin (-0.22, 0.77)
RV: biomass elasmobranchs (-0.23, 0.15)
Snow crab: mature female mean size (-0.32, -0.63)
Snow crab: mature male mean size (-0.39, -0.75)
CPR: dinoflagellates (-0.4, 0.55)
Landed value: shellfish (-0.41, 0.53)
SSE: temperature mean (-0.45, -0.11)
GDP: oil and gas (-0.46, -0.66)
RV: species-area intercept (-0.46, -0.47)
Landings: snow crab (-0.47, 0.22)
CPR: colour (-0.51, 0.81)
Temperature: Sable Is. (-0.56, 0.05)
Landed value: snow crab (-0.6, 0.25)
Seismic 3D: km^2 (-0.6, -0.09)
CPR: diatoms (-0.64, 0.66)
Employment per total landings (-0.77, 0.37)
RV: species-area exponent (-0.85, 0.02)
Shrimp: abundance index (-0.86, 0)
Snow crab: landings (-0.86, -0.48)
NS: Population size (-0.86, 0.12)
NS: % attending university (-0.91, -0.24)
No. shellfish closures (-0.91, 0.41)
RV: groundfish SMR (-0.92, 0.01)
RV: No. taxa predicted (-0.93, -0.26)
GDP: NS total (-0.93, -0.52)
NS: % 65 and older (-0.94, -0.11)
Seal abundance (-0.97, -0.27)
1960
1970
1980
1990
2000
2010
Years

Figure 12: Sorted ordination of anomalies of key social, economic and ecological patterns on the Scotian Shelf relevant to snow crab. Red indicates levels below the mean and green is above the mean. Open boxes indicate no data.

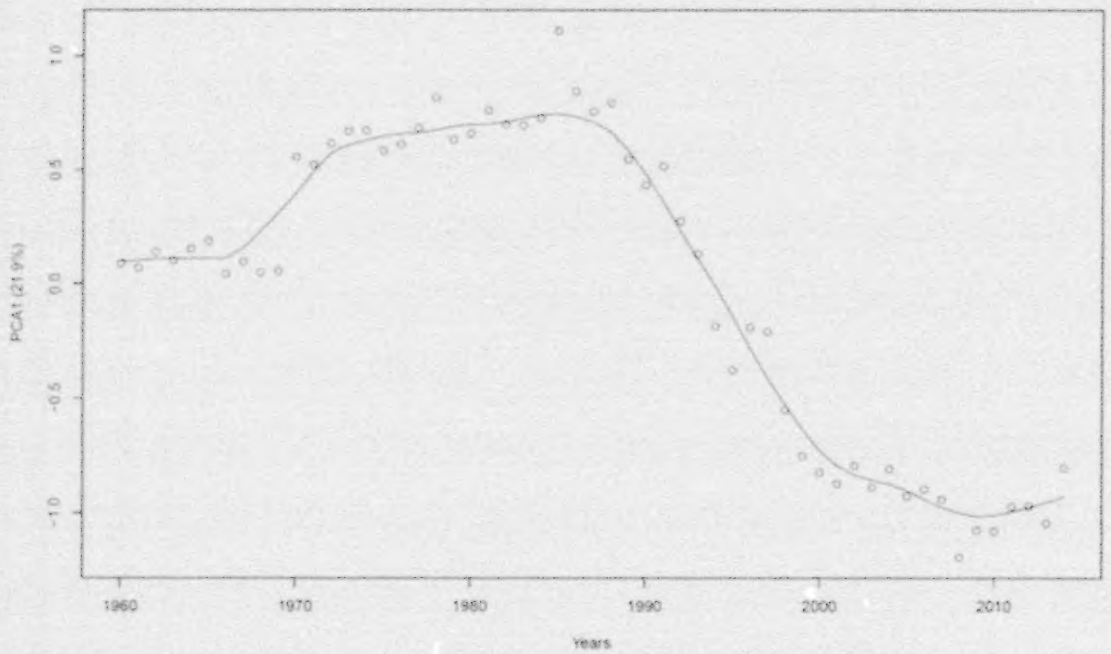


Figure 13: First axis of variations in ordination of the anomalies of the social, economic, and ecological patterns on the Scotian Shelf. Note the strong variability observed near the time of the groundfish fishery collapse in the early-1990s.

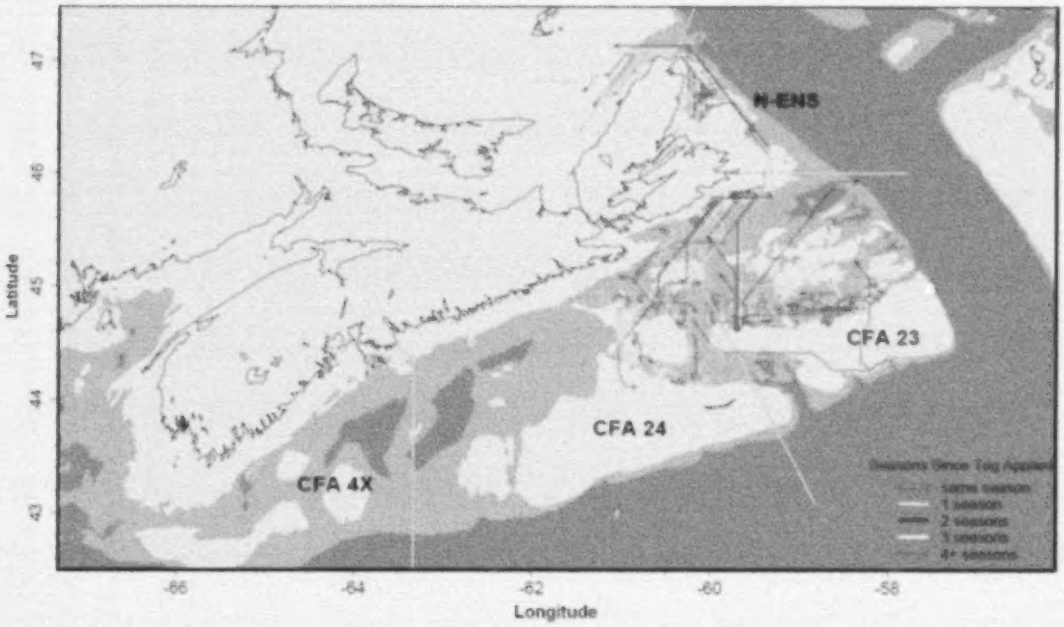


Figure 14: Map of movements for tagged terminally moulted commercial snow crab on the Scotian Shelf with movements between mark and recapture locations constrained to the shortest path within depth contours of 60 and 280 m.

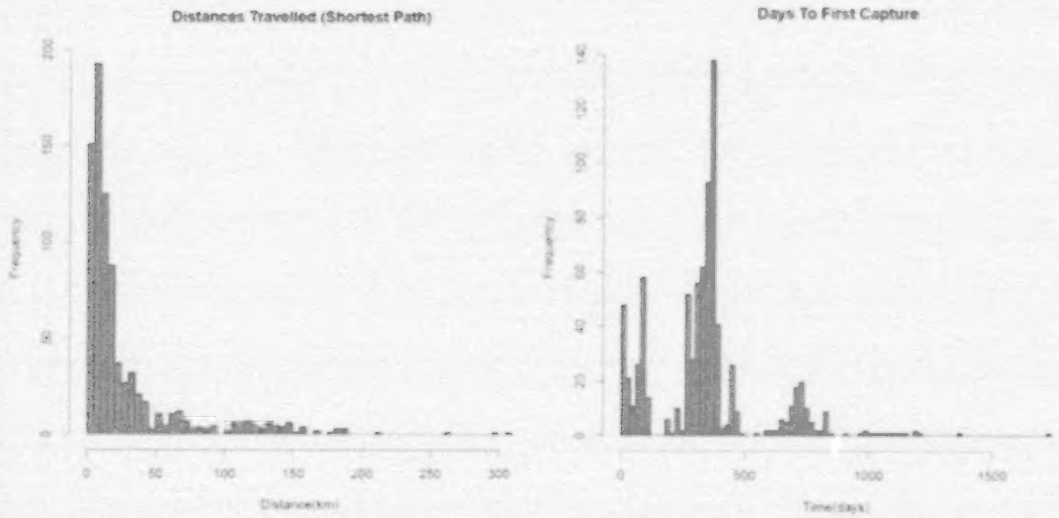


Figure 15: (Left) Distance travelled by tagged snow crab on the Scotian Shelf between 2005 and 2014. (Right) Return intervals in days between initial release and first capture of snow crab tagged on the Scotian Shelf. Periodicity in time intervals are explained by recaptures occurring during seasonal fishing operations.

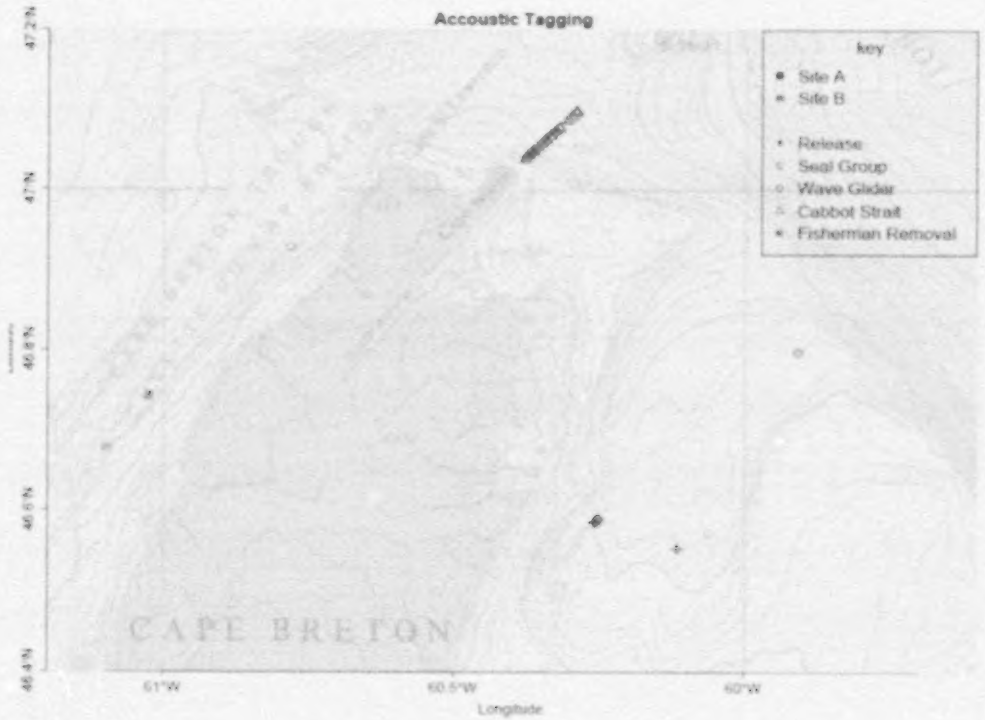


Figure 16: Map of release and detection sites of acoustic tags applied to 27 terminally moulted commercial snow crab.

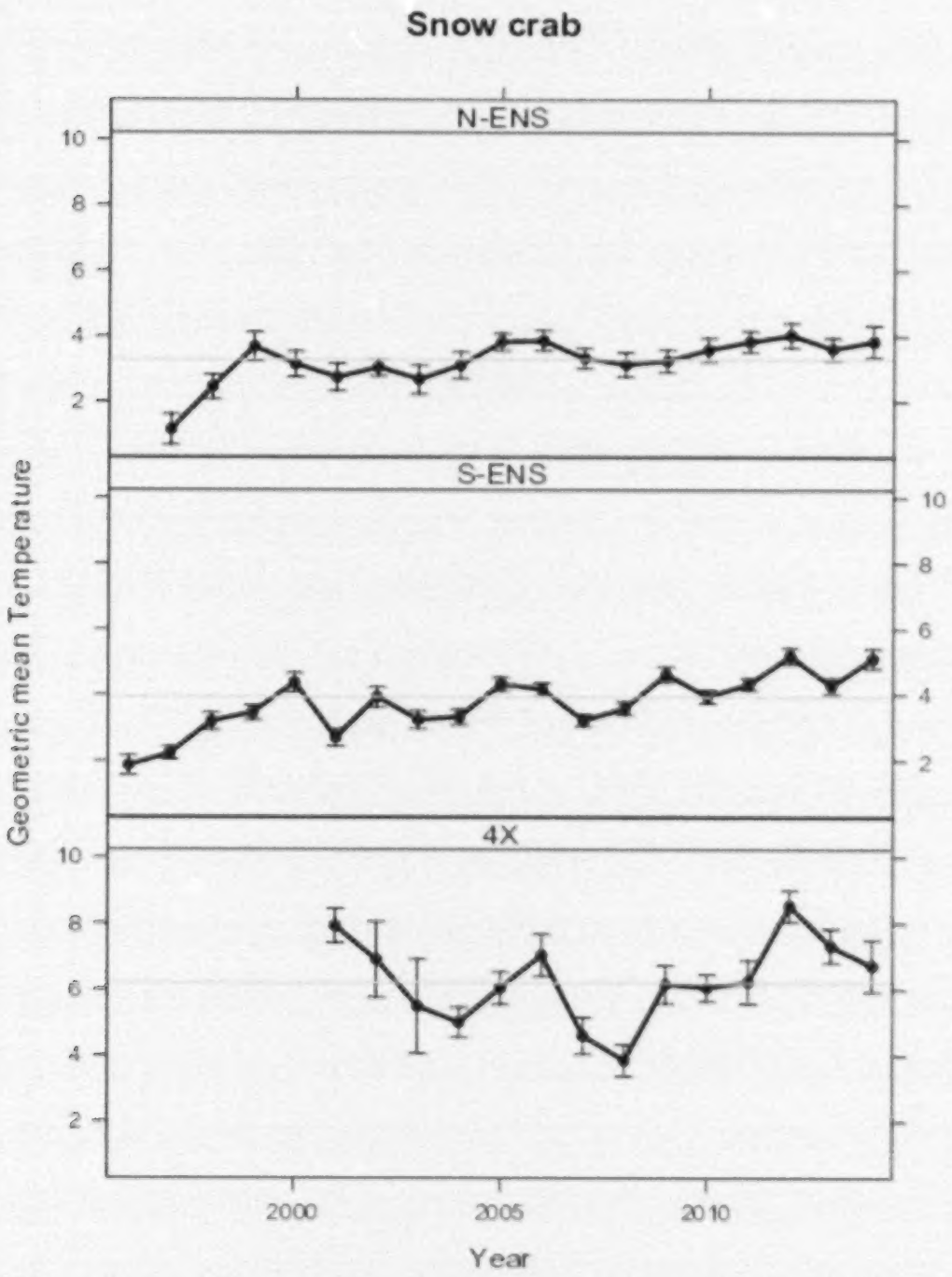


Figure 17: Variations in geometric mean bottom temperature observed during the Scotian Shelf snow crab survey by year. The horizontal line indicates the long-term median temperature within each subarea. Error bars are 1 geometric standard deviation.

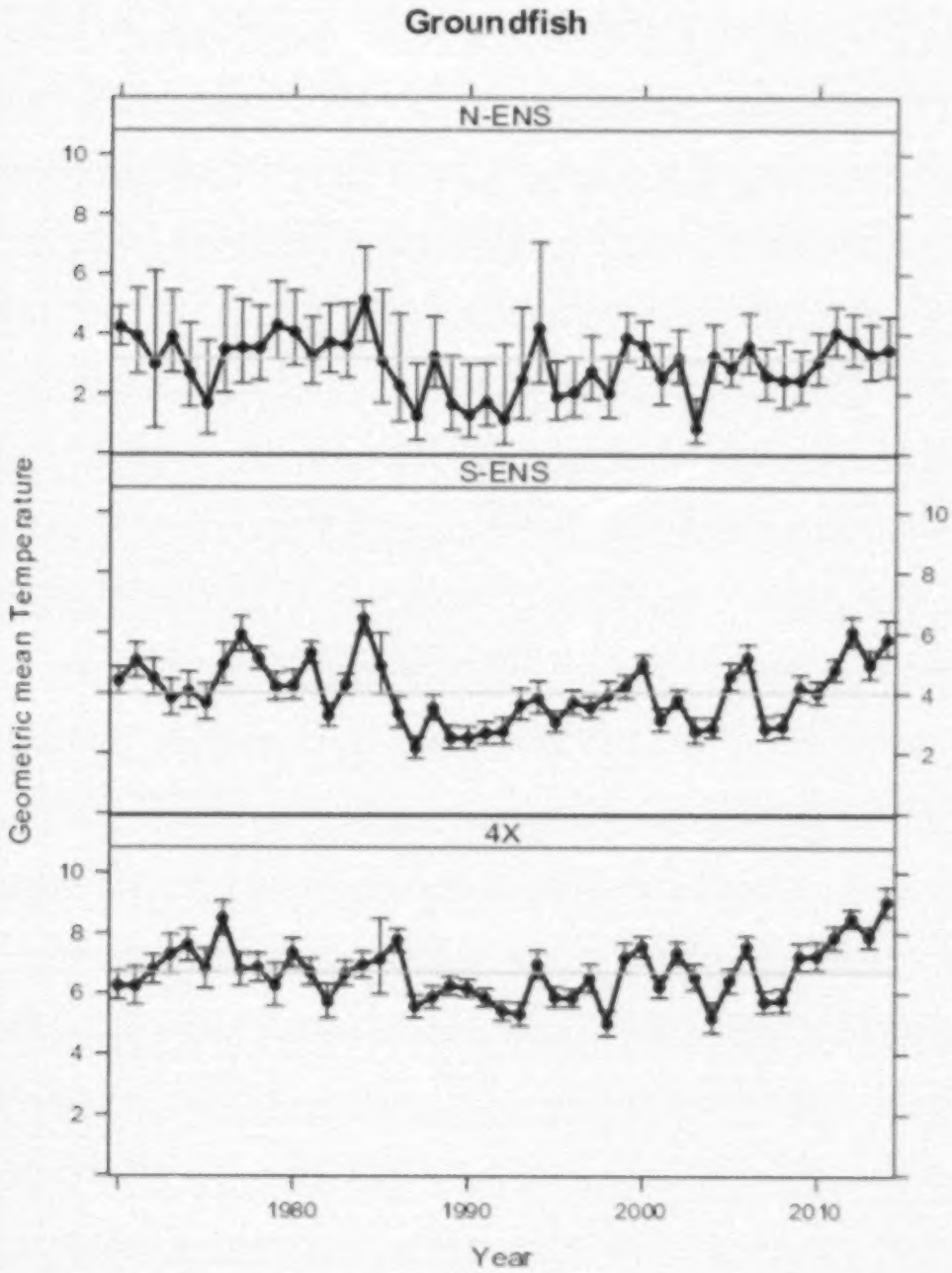


Figure 18: Variations in geometric mean bottom temperature observed during the summer DFO R/V groundfish survey by year. The horizontal line indicates the long-term median temperature within each subarea. Error bars represent one geometric standard deviation.

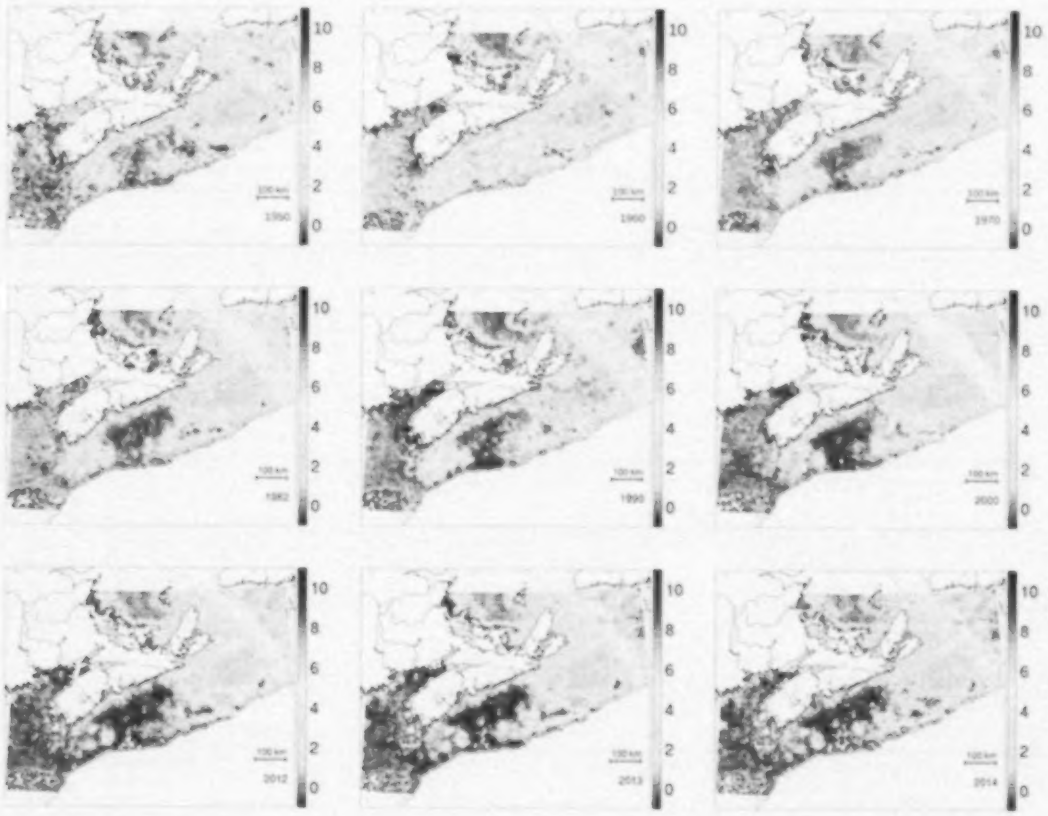


Figure 19: Interpolated mean annual bottom temperatures on the Scotian Shelf for selected years. These interpolations use all available water temperature data collected in the area including groundfish surveys, snow crab survey and Atlantic Zonal Monitoring Program (AZMP) monitoring stations.

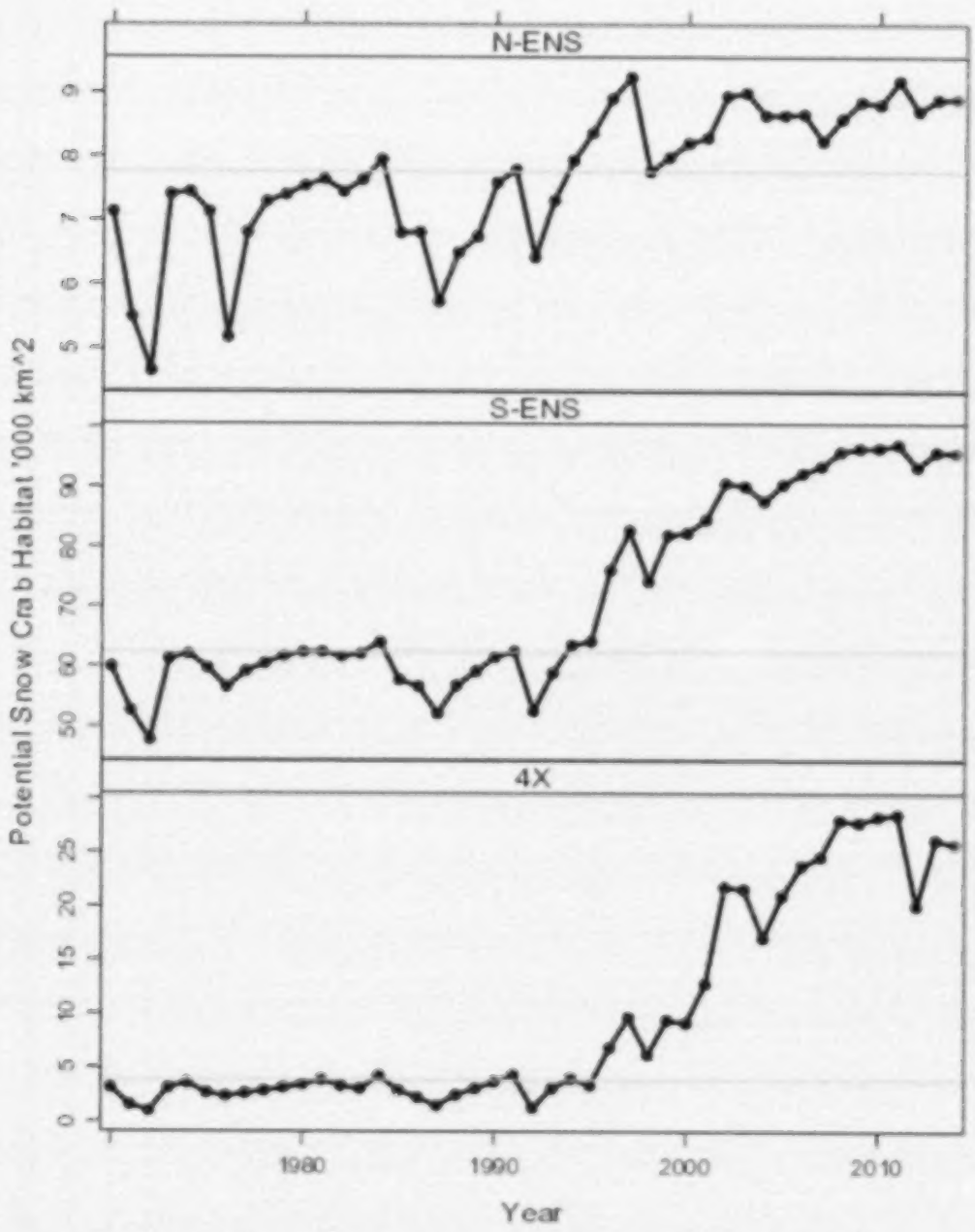


Figure 20: Annual variations in the surface area of potential snow crab habitat. The horizontal line represents the long-term median surface area with each sub area. The estimates for the period from 1998-present are based upon snow crab survey data, while those prior to 1998 are projected using incomplete data and, therefore, are less reliable. Within each subarea, the 2013 habitat area was estimated using the mean of the past five years (red dots).

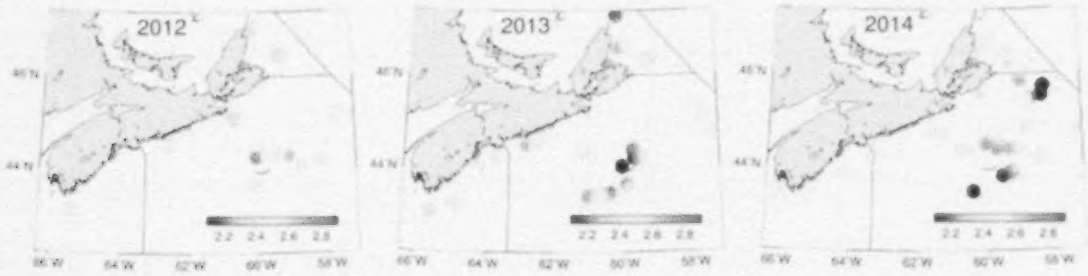


Figure 21: Maps of locations and density of potential predators of snow crab: Atlantic halibut in 2012-2014. Scale is $log_{10}(n/km^2)$.

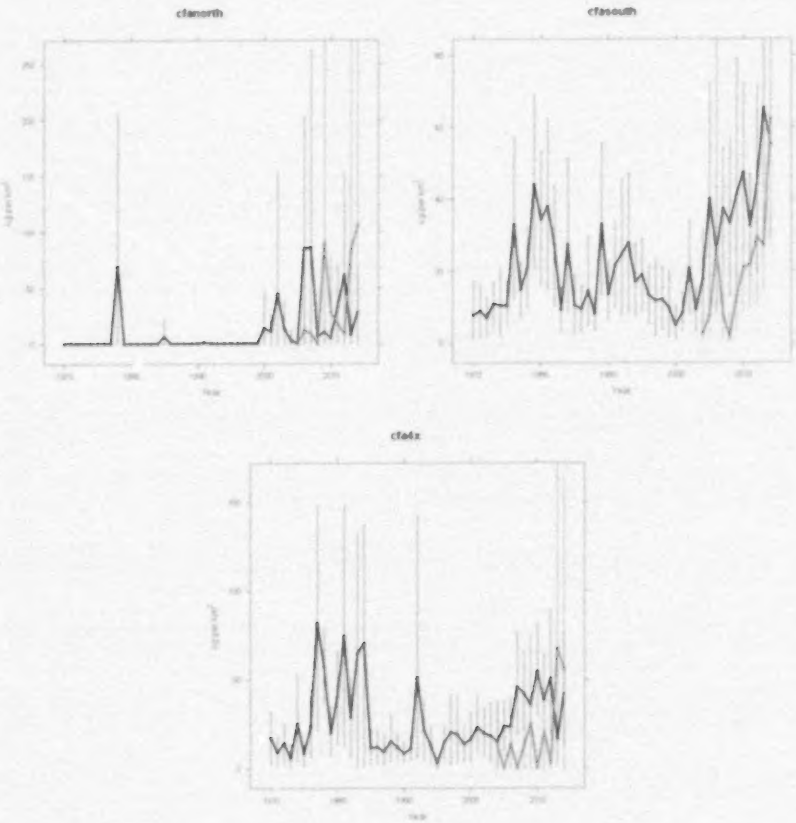


Figure 22: Trends in biomass for potential predators of snow crab on the Scotian Shelf: Atlantic halibut. Black line represents trends from the summer DFO R/V groundfish survey where N-ENS is estimated from strata 440-442, S-ENS is depicted from strata 443-467 and 4X is depicted by strata 470-483. Red line represents the trends from the annual snow crab survey. In both vertical lines are 95% confidence intervals estimated by bootstrapping.

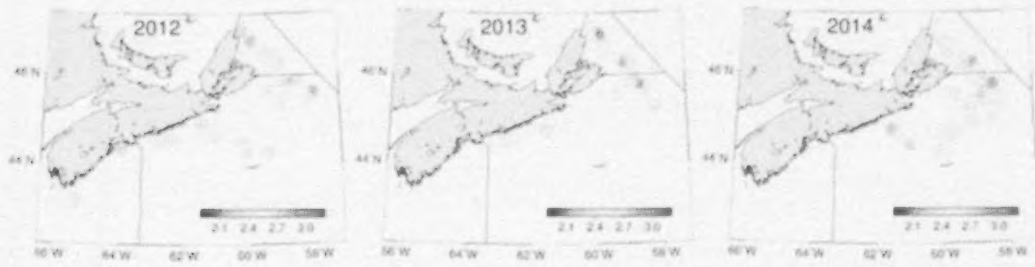


Figure 23: Maps of locations and density of potential predators of snow crab: Atlantic wolffish in 2012-2014. Scale is $\log_{10}(n/km^2)$.

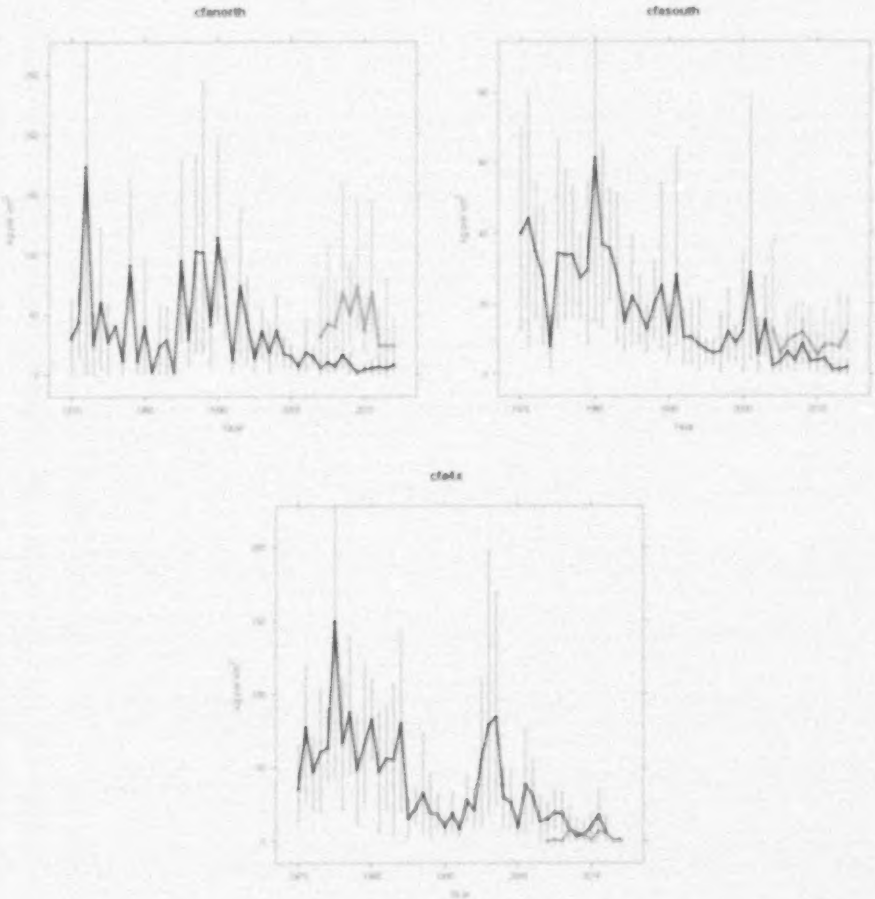


Figure 24: Trends in biomass for potential predators of snow crab on the Scotian Shelf: Atlantic wolffish. Black line represents trends from the summer DFO R/V groundfish survey where N-ENS is estimated from strata 440-442, S-ENS is depicted from strata 443-467 and 4X is depicted by strata 470-483. Red line represents the trends from the annual snow crab survey. In both vertical lines are 95% confidence intervals estimated by bootstrapping.

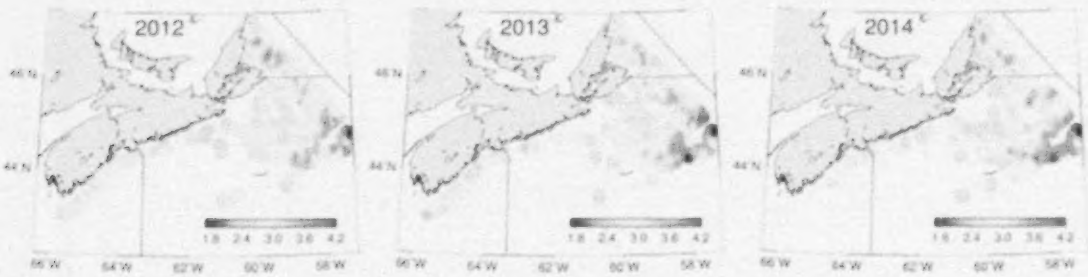


Figure 25: Maps of locations and density of potential predators of snow crab: Thorny skate in 2012-2014. Scale is $log_{10}(n/km^2)$.

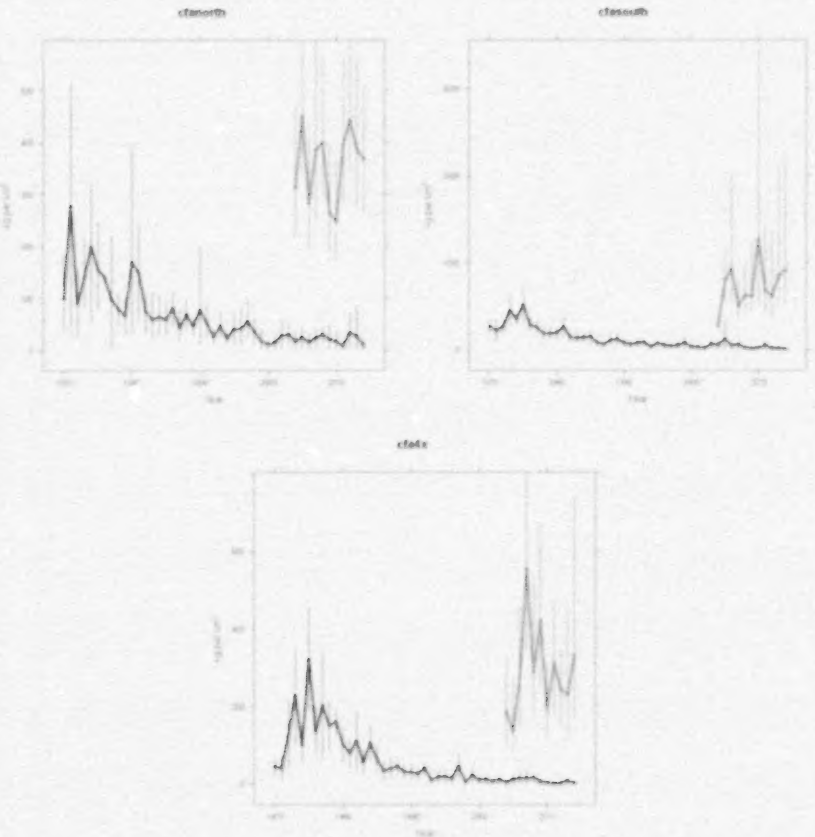


Figure 26: Trends in biomass for potential predators of snow crab on the Scotian Shelf: Thorny skate. Black line represents trends from the summer DFO R/V groundfish survey where N-ENS is estimated from strata 440-442, S-ENS is depicted from strata 443-467 and 4X is depicted by strata 470-483. Red line represents the trends from the annual snow crab survey. In both vertical lines are 95% confidence intervals estimated by bootstrapping.

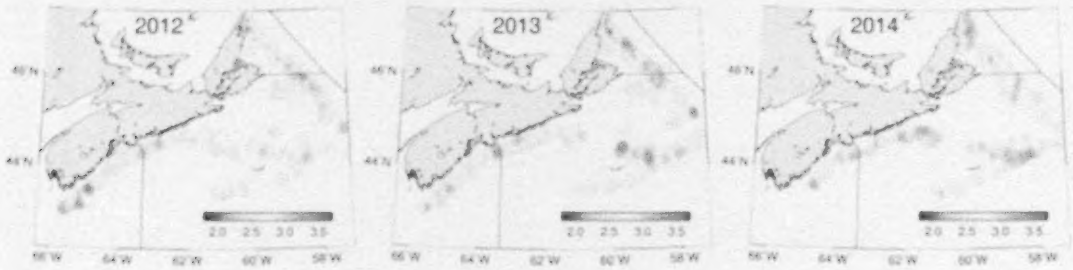


Figure 27: Maps of locations and density of potential predator of snow crab: Smooth skate in 2012-2014. Scale is $log_{10}(n/km^2)$.

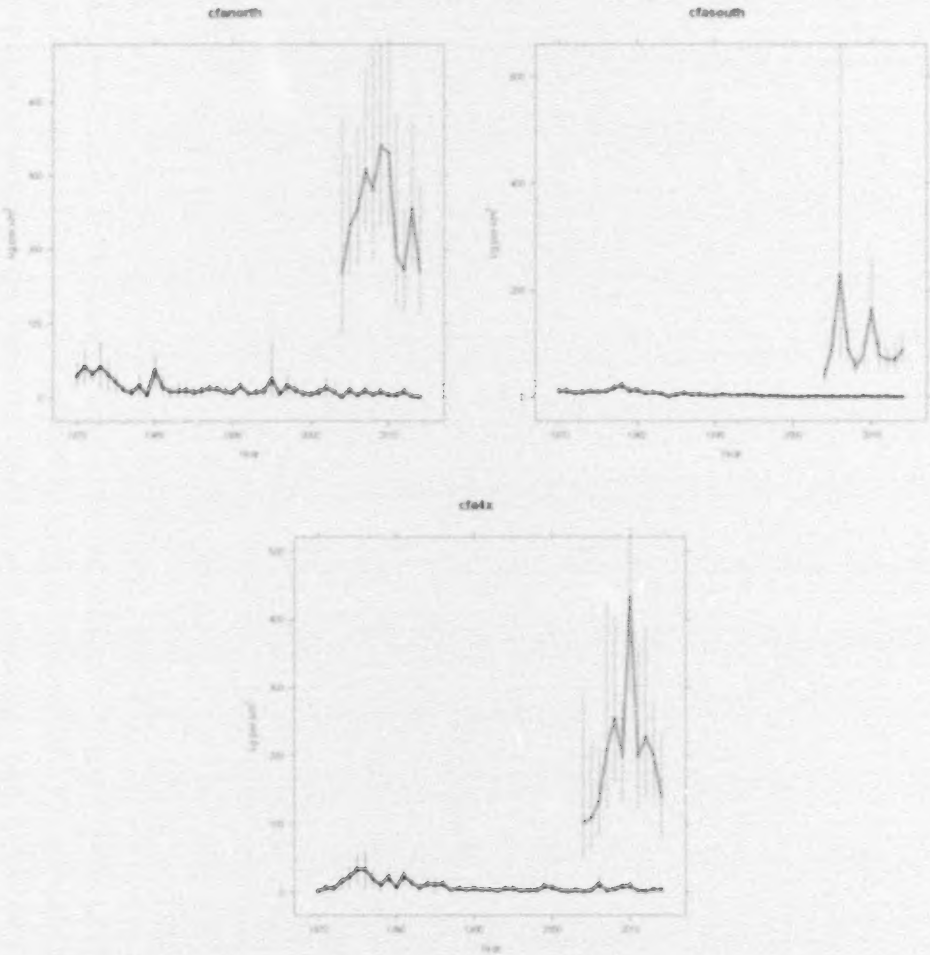


Figure 28: Trends in biomass for potential predators of snow crab on the Scotian Shelf: Smooth skate. Black line represents trends from the summer DFO R/V groundfish survey where N-ENS is estimated from strata 440-442, S-ENS is depicted from strata 443-467 and 4X is depicted by strata 470-483. Red line represents the trends from the annual snow crab survey. In both vertical lines are 95% confidence intervals estimated by bootstrapping.

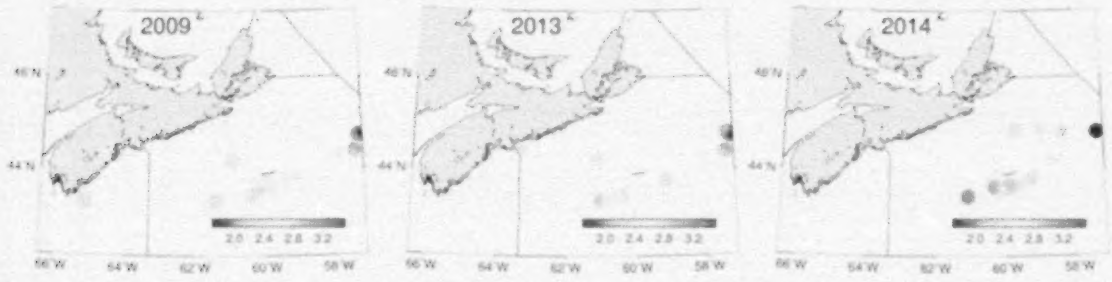


Figure 29: Maps of locations and density of potential predators of snow crab: Winter skate in 2012-2014. Scale is $log_{10}(n/km^2)$.

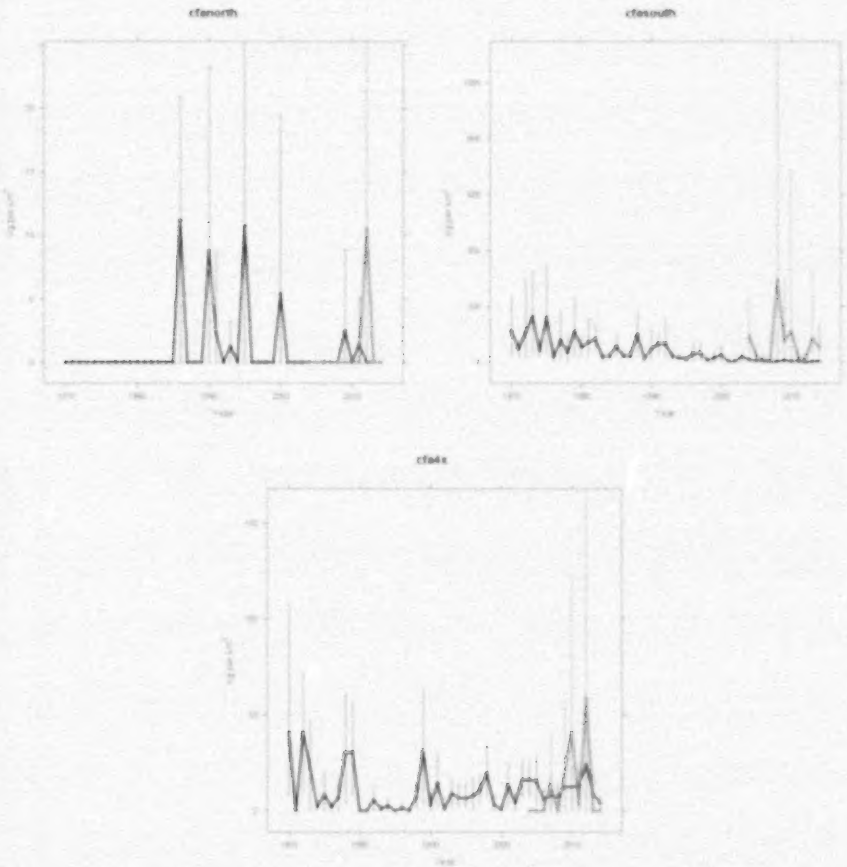


Figure 30: Trends in biomass for potential predators of snow crab on the Scotian Shelf: Winter skate. Black line represents trends from the summer DFO R/V groundfish survey where N-ENS is estimated from strata 440-442, S-ENS is depicted from strata 443-467 and 4X is depicted by strata 470-483. Red line represents the trends from the annual snow crab survey. In both vertical lines are 95% confidence intervals estimated by bootstrapping.

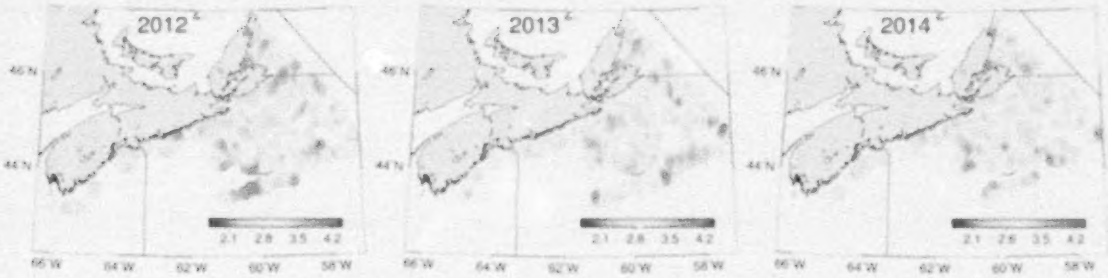


Figure 31: Maps of locations and density of potential predators of snow crab: Atlantic cod in 2012-2014. Scale is $log_{10}(n/km^2)$.

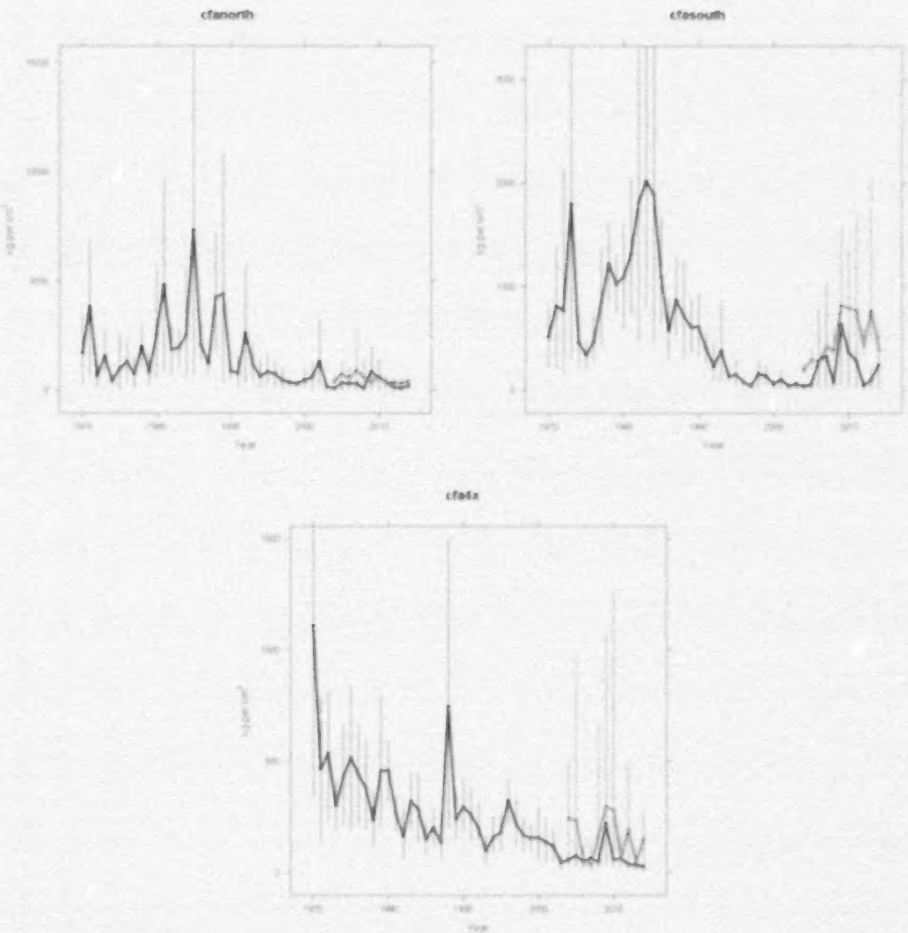


Figure 32: Trends in biomass for potential predators of snow crab on the Scotian Shelf: Atlantic cod. Black line represents trends from the summer DFO R/V groundfish survey where N-ENS is estimated from strata 440-442, S-ENS is depicted from strata 443-467 and 4X is depicted by strata 470-483. Red line represents the trends from the annual snow crab survey. In both vertical lines are 95% confidence intervals estimated by bootstrapping.

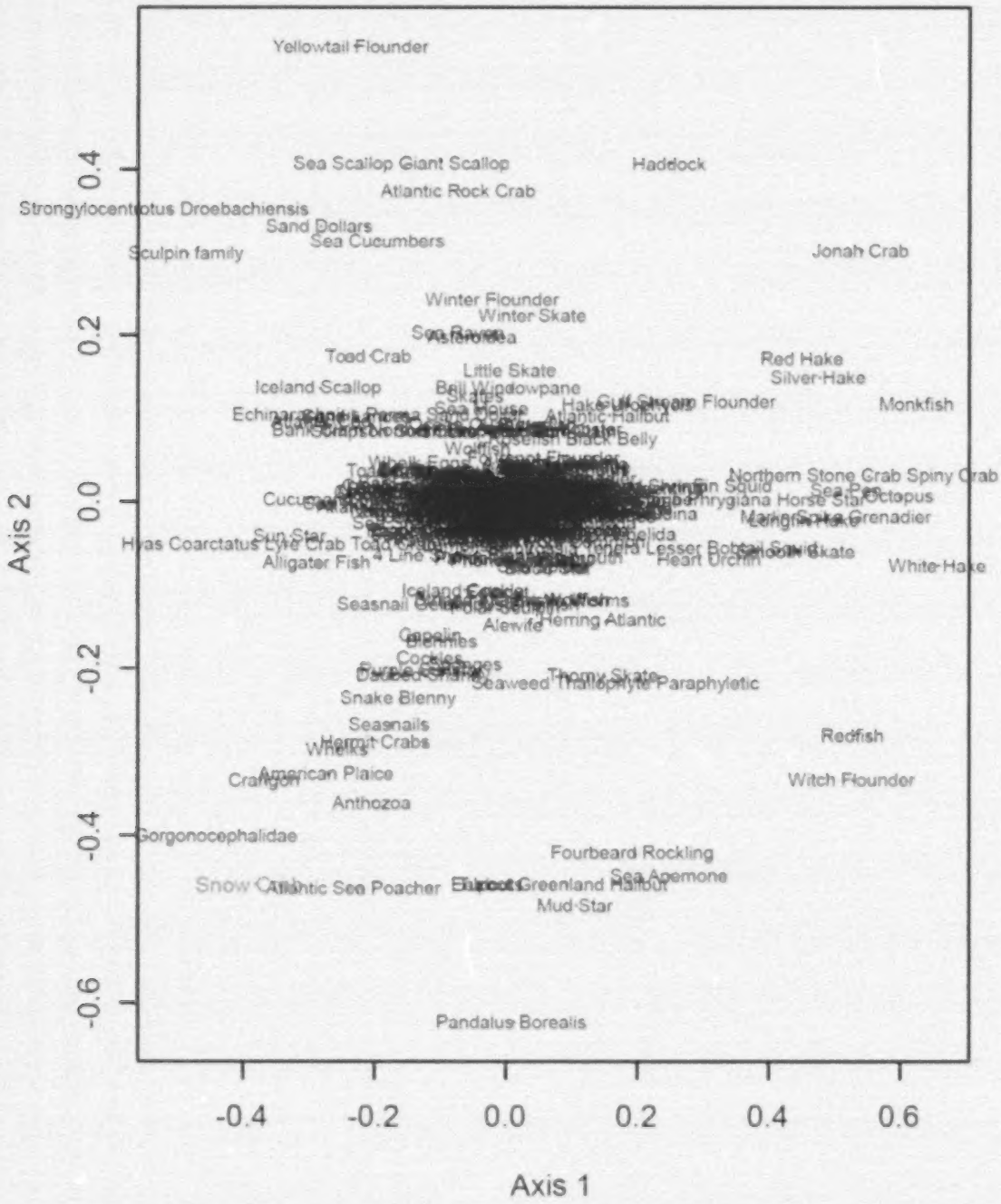


Figure 33: Ordination from a Principle Coordinates Analysis of log-transformed numerical densities based on Pearson correlation matrices.

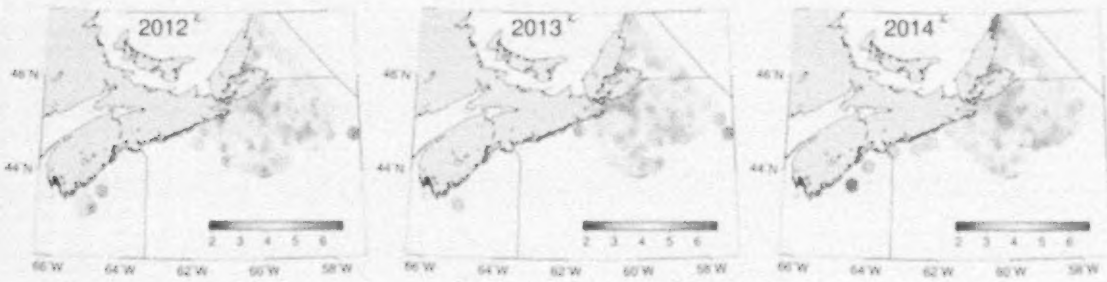


Figure 34: Maps of locations and density of potential prey of snow crab: Northern shrimp in 2012-2014. Scale is $log_{10}(n/km^2)$.

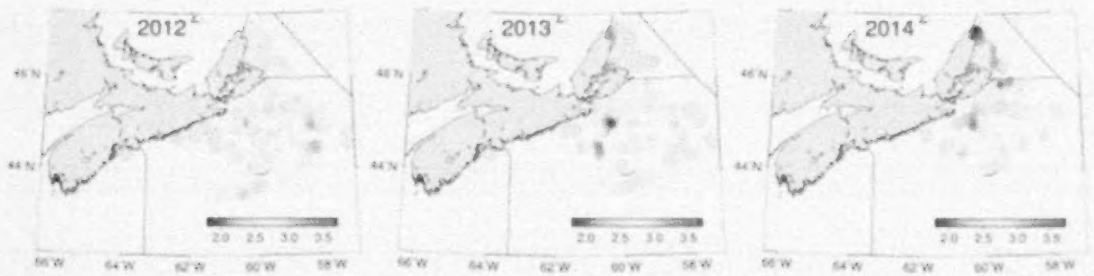


Figure 35: Maps of locations and density of potential competition of snow crab: Lesser toad crab in 2012-2014. Scale is $log_{10}(n/km^2)$.

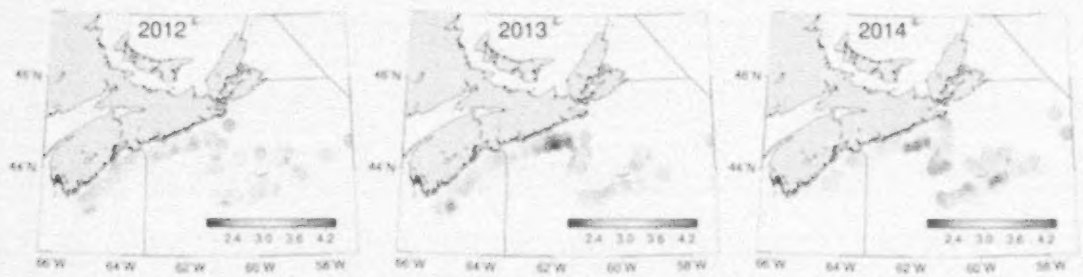


Figure 36: Maps of locations and density of potential competition of snow crab: Jonah crab in 2012-2014. Scale is $log_{10}(n/km^2)$.

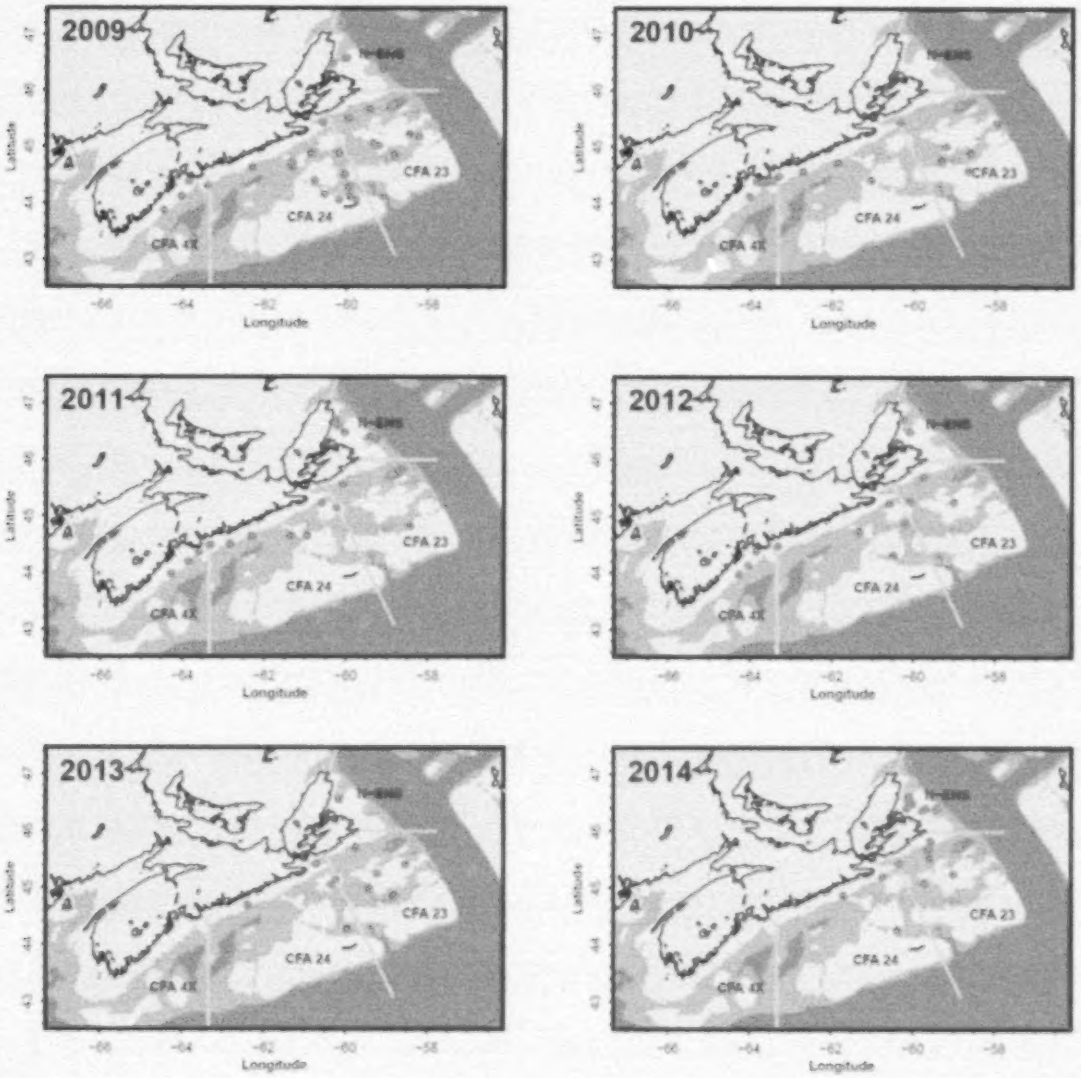


Figure 37: Maps of annual locations of bitter crab disease (BCD) observations during the snow crab survey.

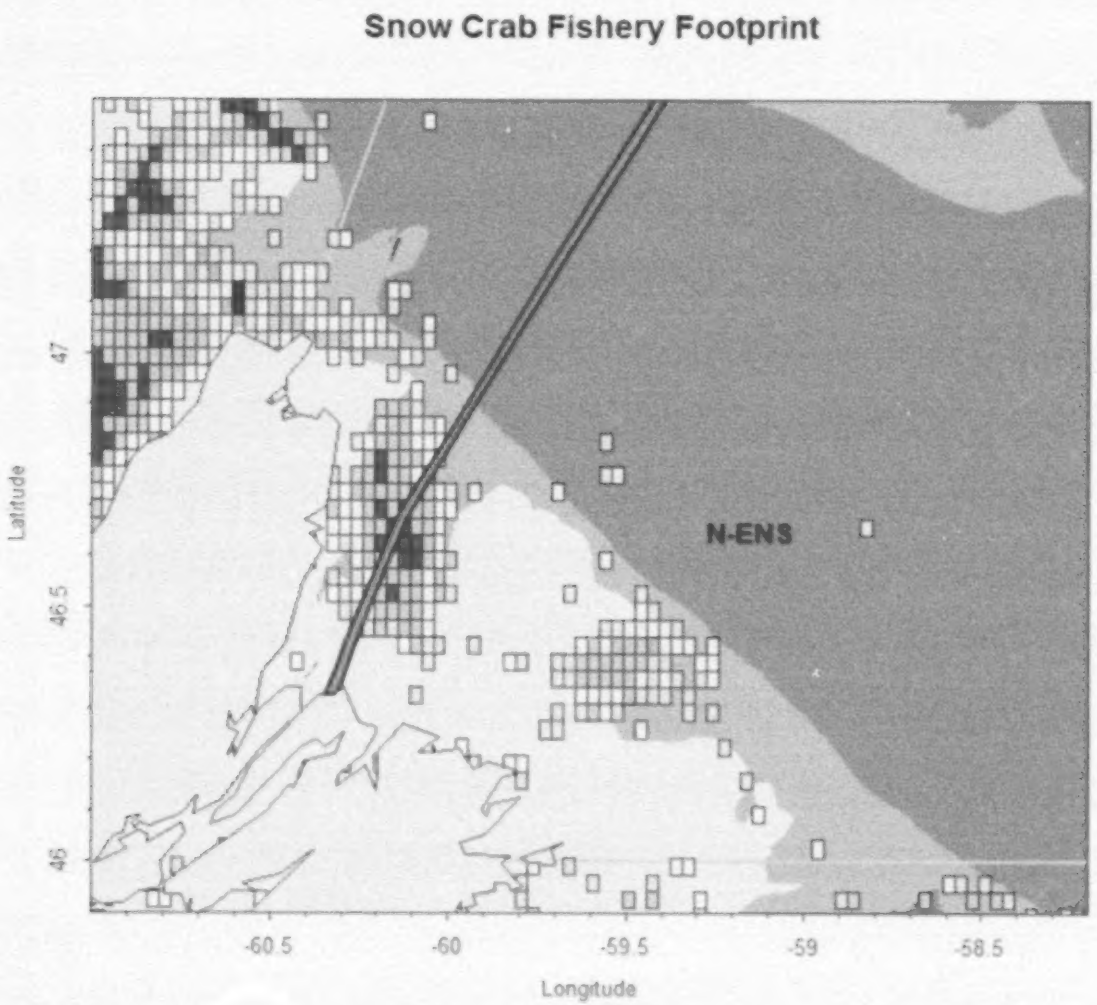


Figure 38: Fishery footprint map of the N-ENS snow crab fishery using landings data from logbook records between 2006 and 2010. Blue is low, yellow is medium and red is high total landings within each 2-minute square grid. The red line represents the proposed corridor for emplacement of two power transmission cables.

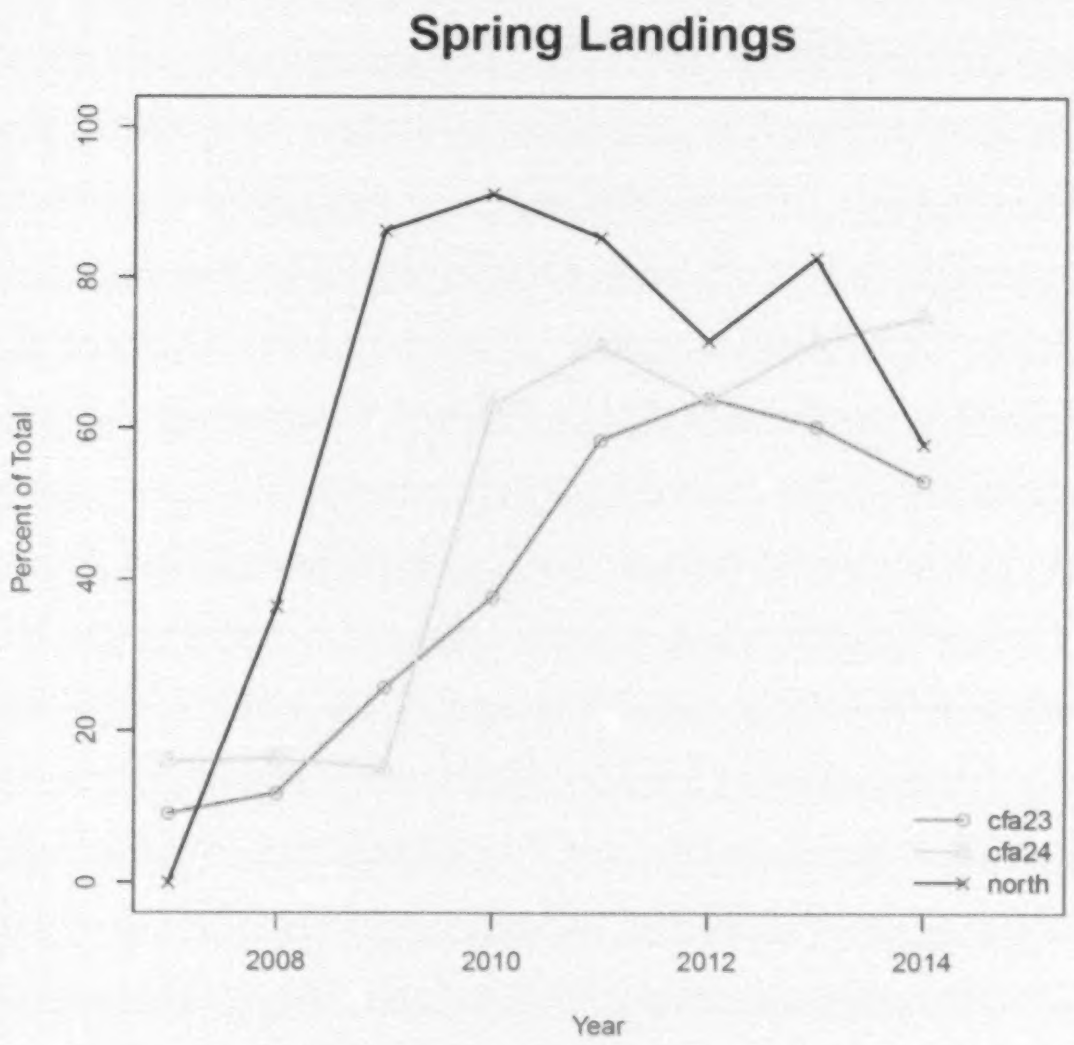


Figure 39: The percent of total annual snow crab landings caught during the months of April–June (Spring) separated by snow crab fishing area.

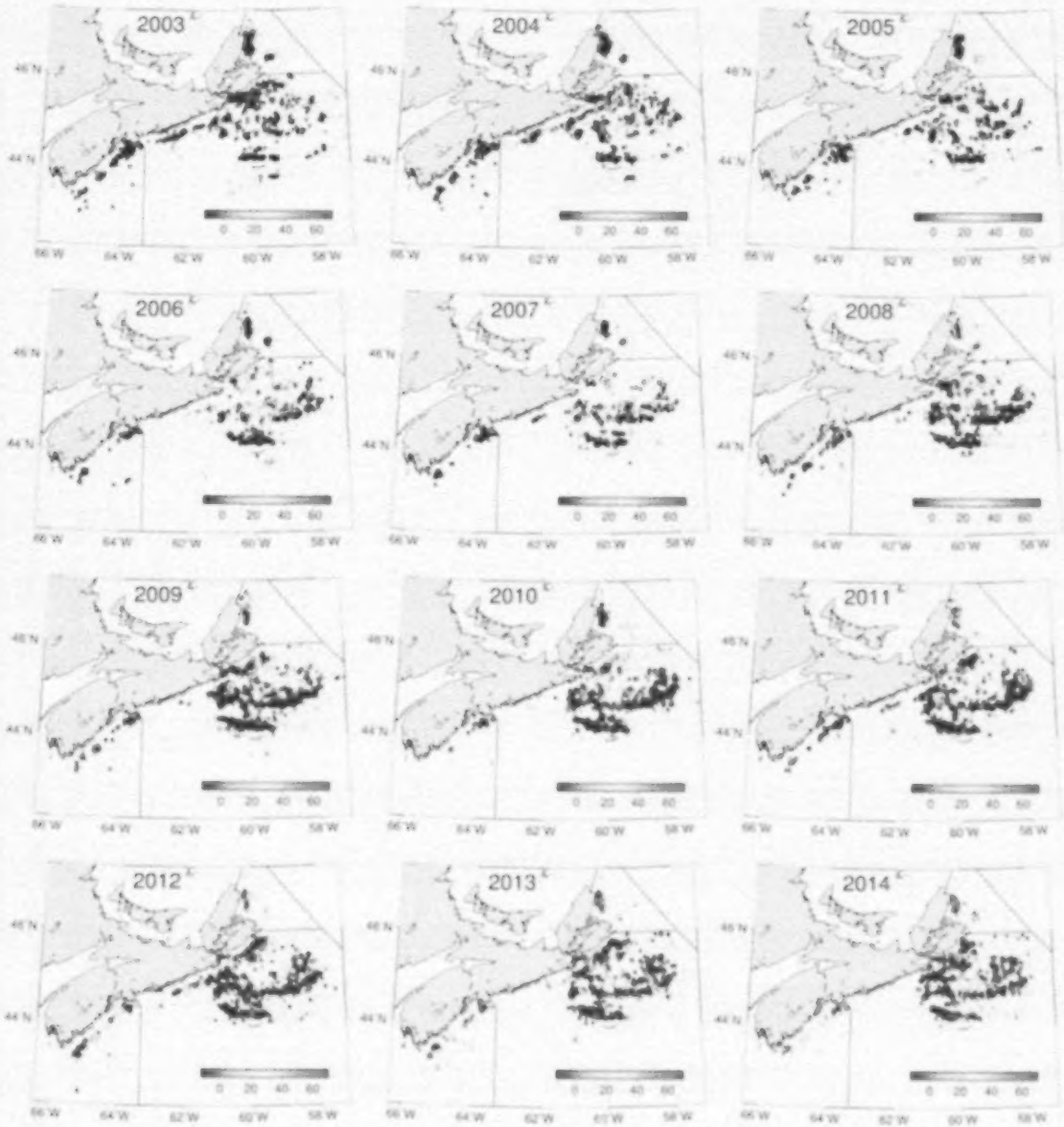


Figure 40: Maps of fishing effort (number of trap hauls per 1-minute grid) from the Scotian Shelf snow crab fisheries logbook data for each of 2003-2014.

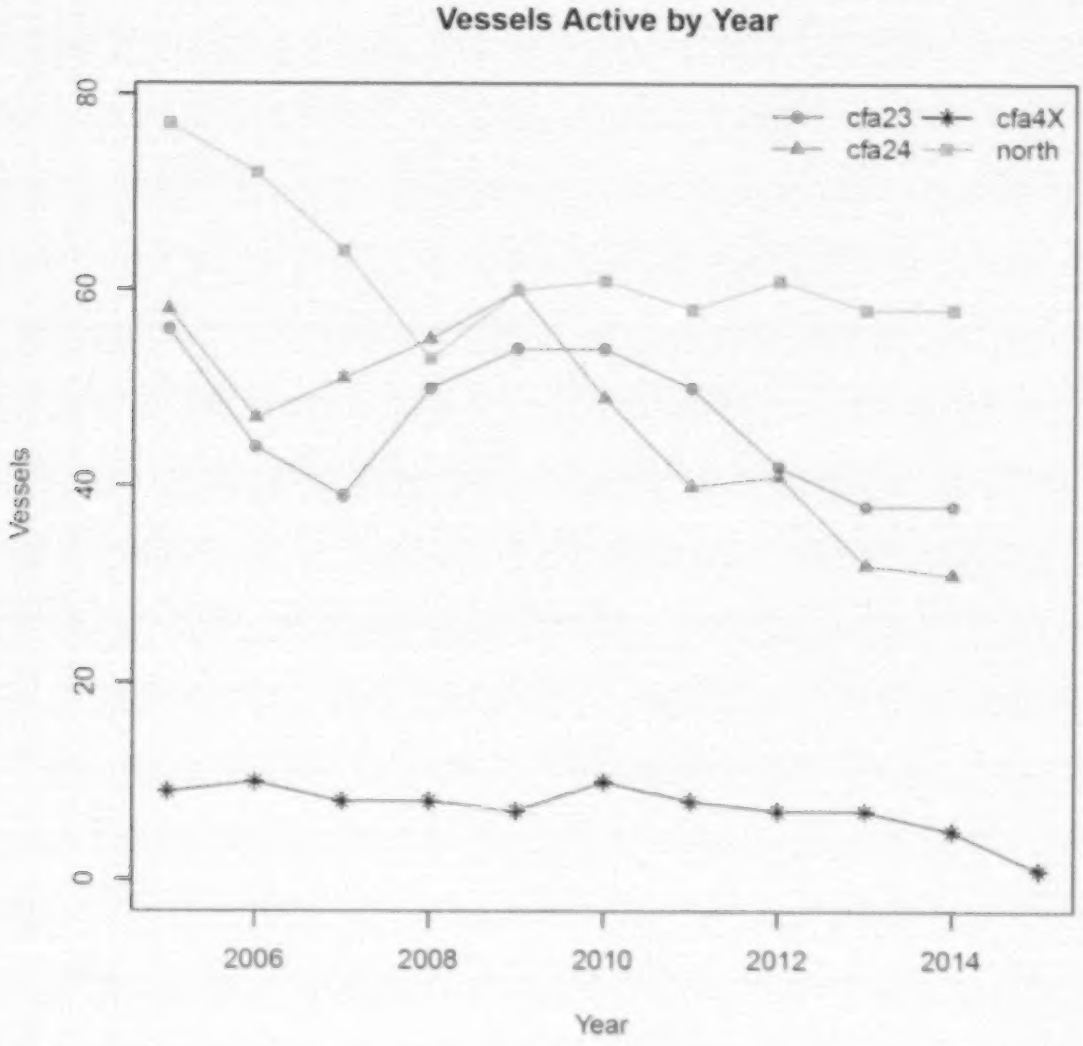


Figure 41: Number of active vessels fishing in each of the Scotian Shelf snow crab fishing areas. S-ENS is separated into CFA23 and CFA24 to maintain consistency with historic information. The number of licenses within each area have been stable since 2004.

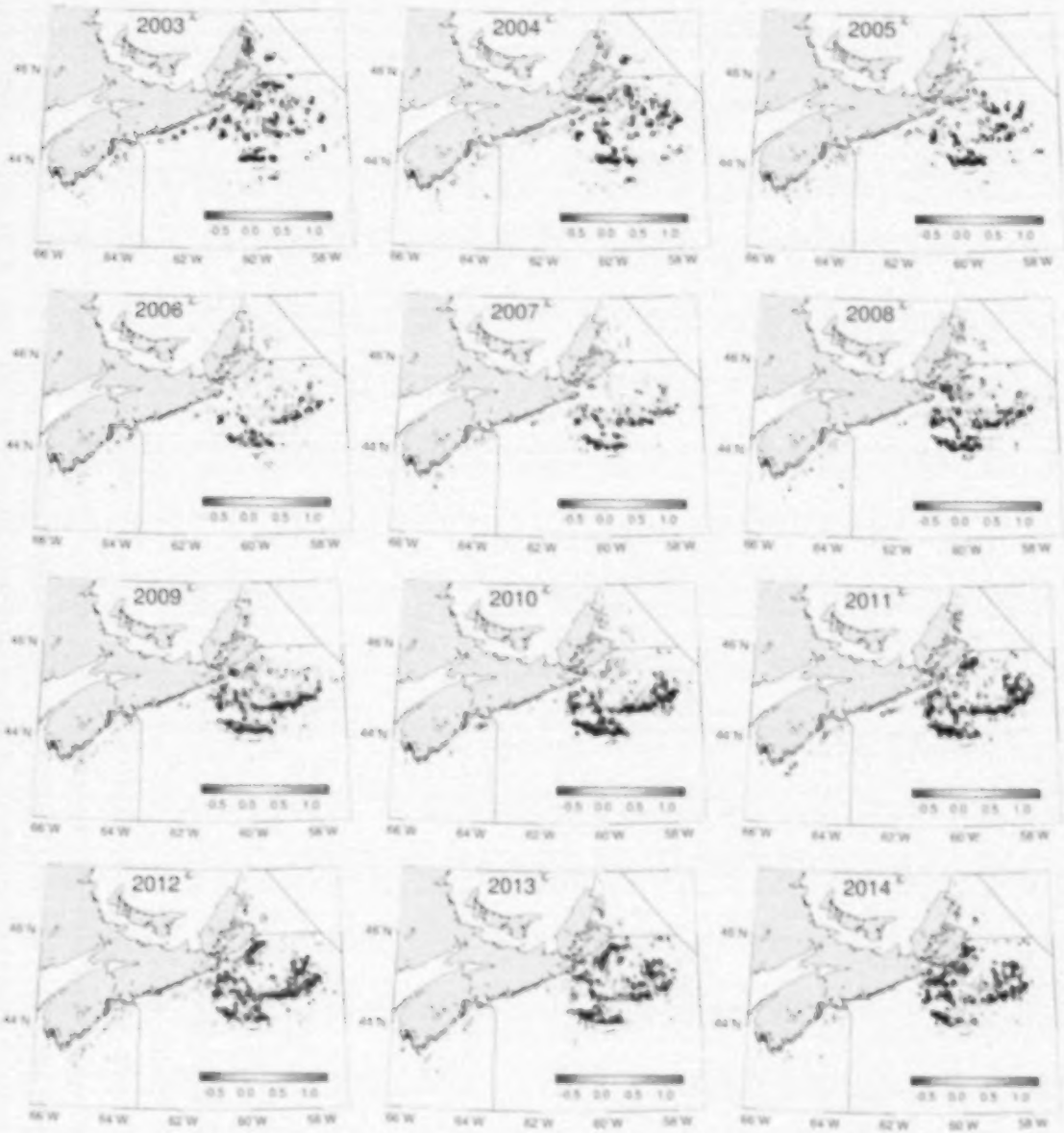


Figure 42: Maps of snow crab landings (log (landings) per 1-minute grid) from the Scotian Shelf snow crab fisheries logbook data for 2003-2014.

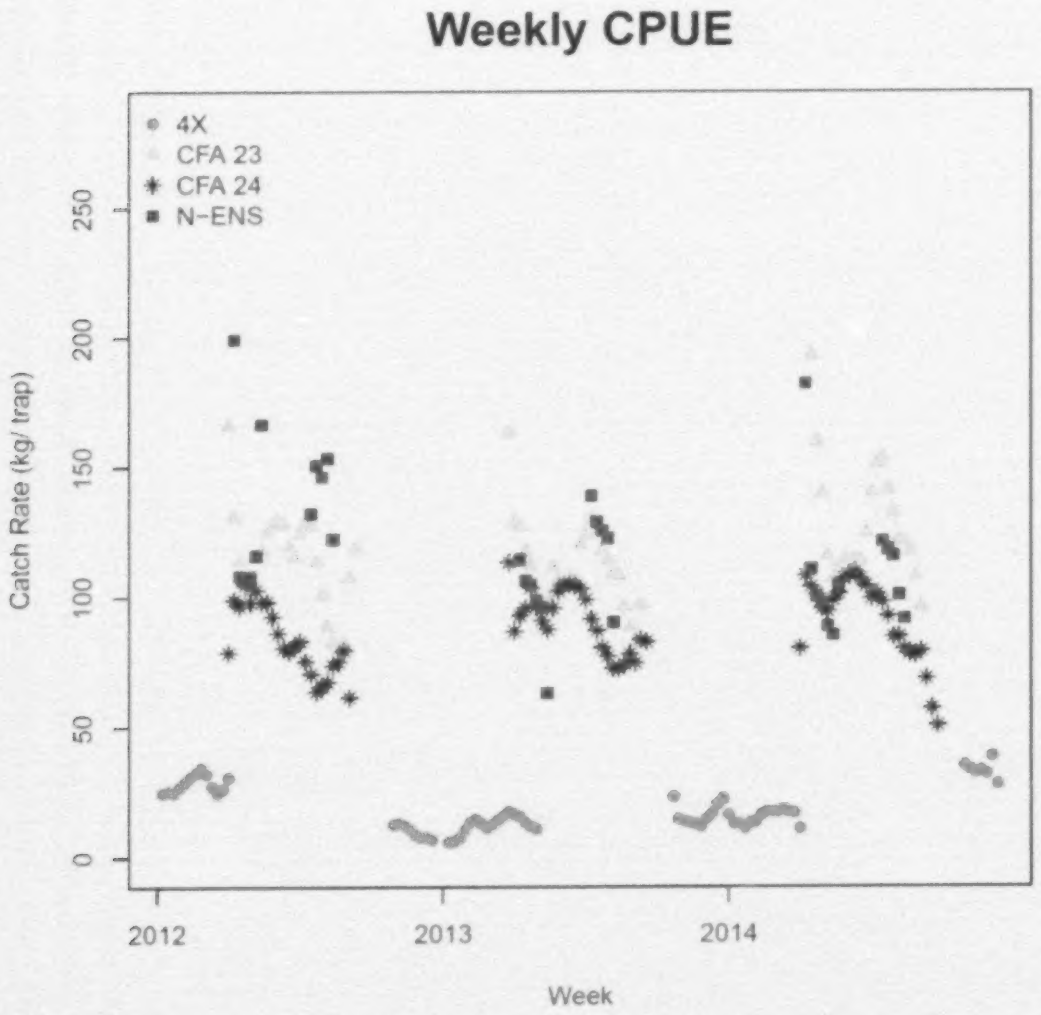


Figure 43: Smoothed catch rates (kg/trap) by week for the past three fishing seasons (2012- 2014). The split season for N-ENS (spring and summer fisheries) create the apparent gap within years.

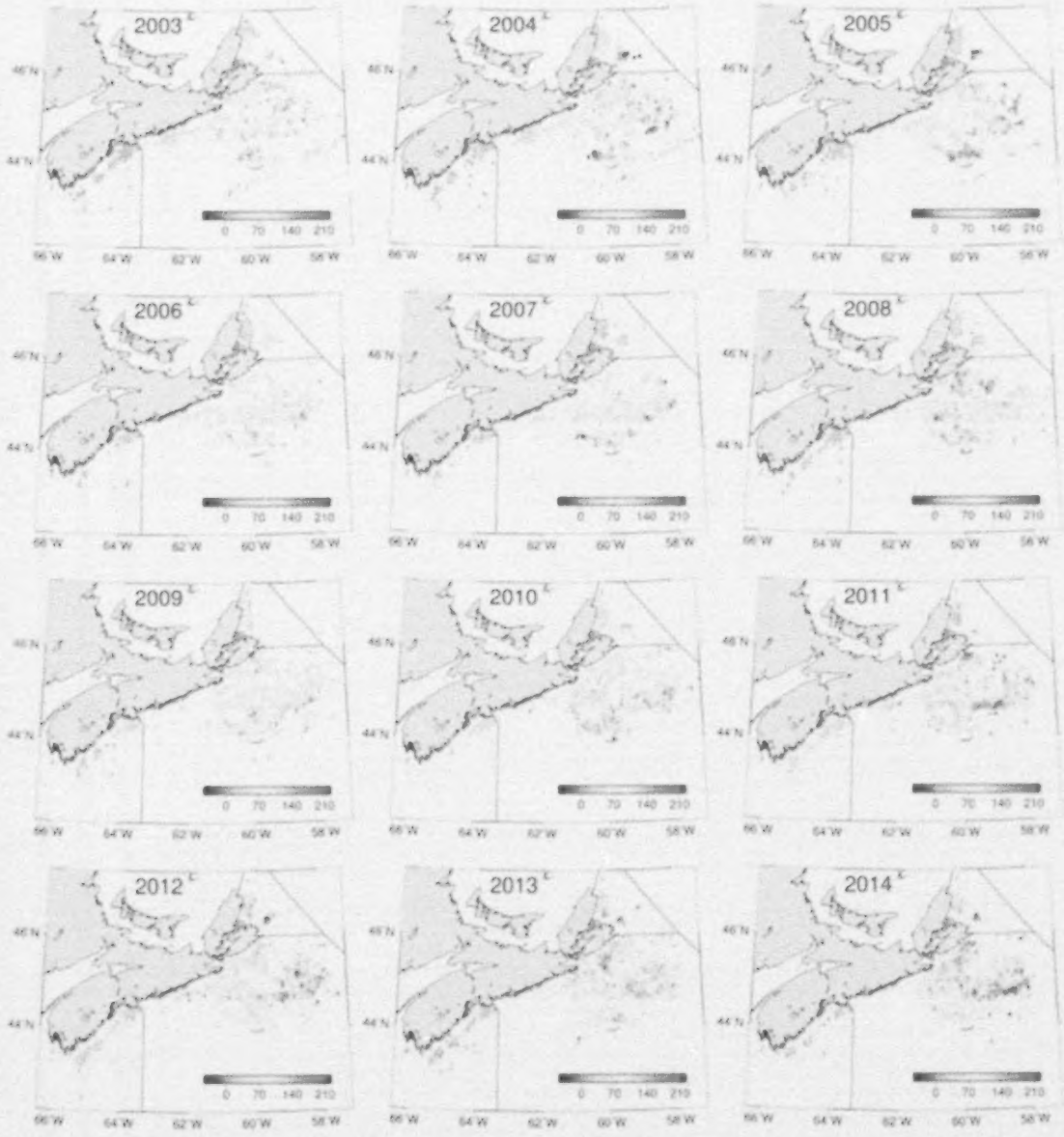


Figure 44: Maps of the distribution of snow crab catch rates (kg per trap per 1-minute grid) from the Scotian Shelf fisheries logbook data for 2003-2014.

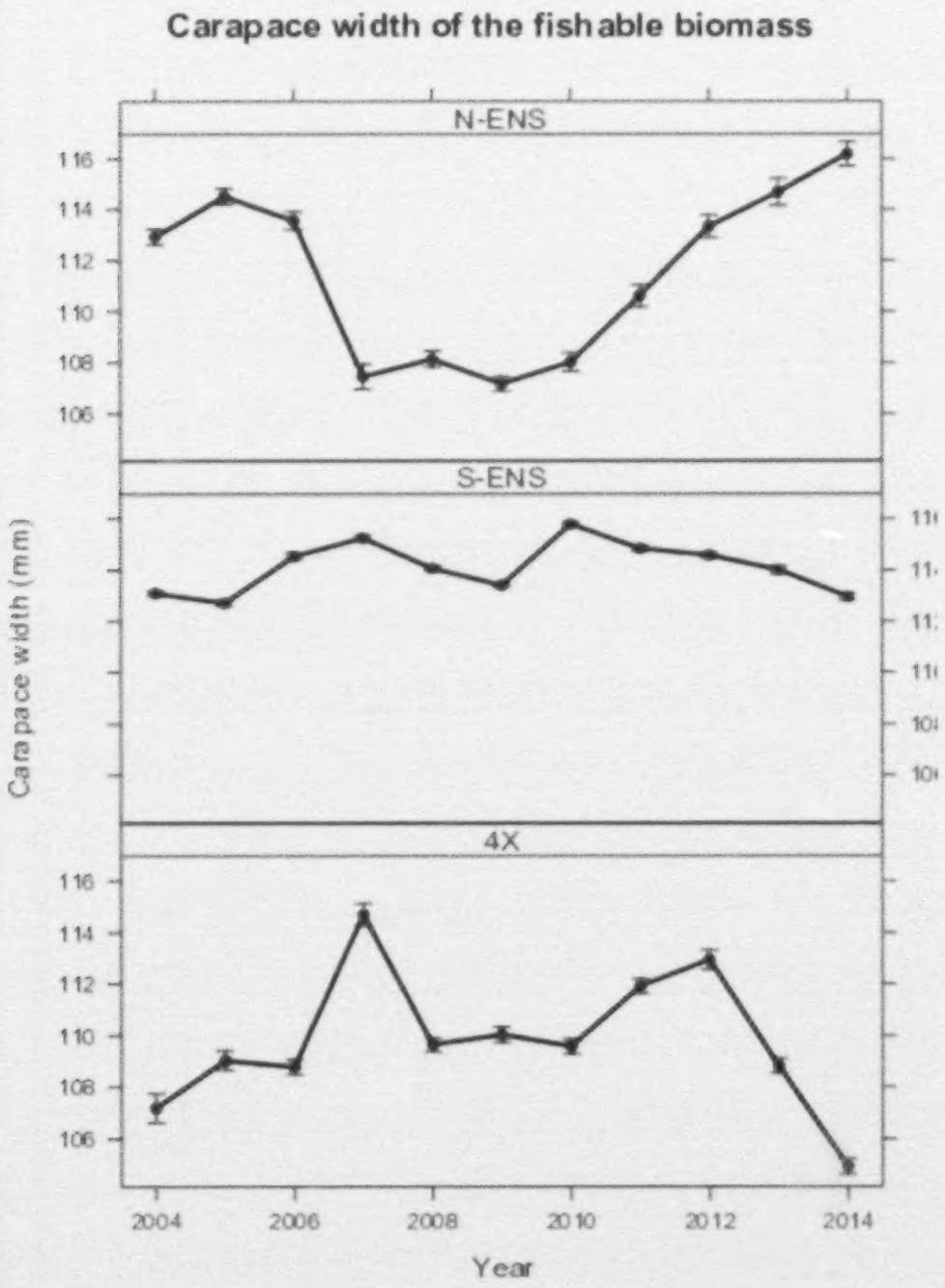


Figure 45: Time series of geometric mean carapace width of commercial crab measured by at-sea-observers. Vertical lines represent 95% confidence intervals.

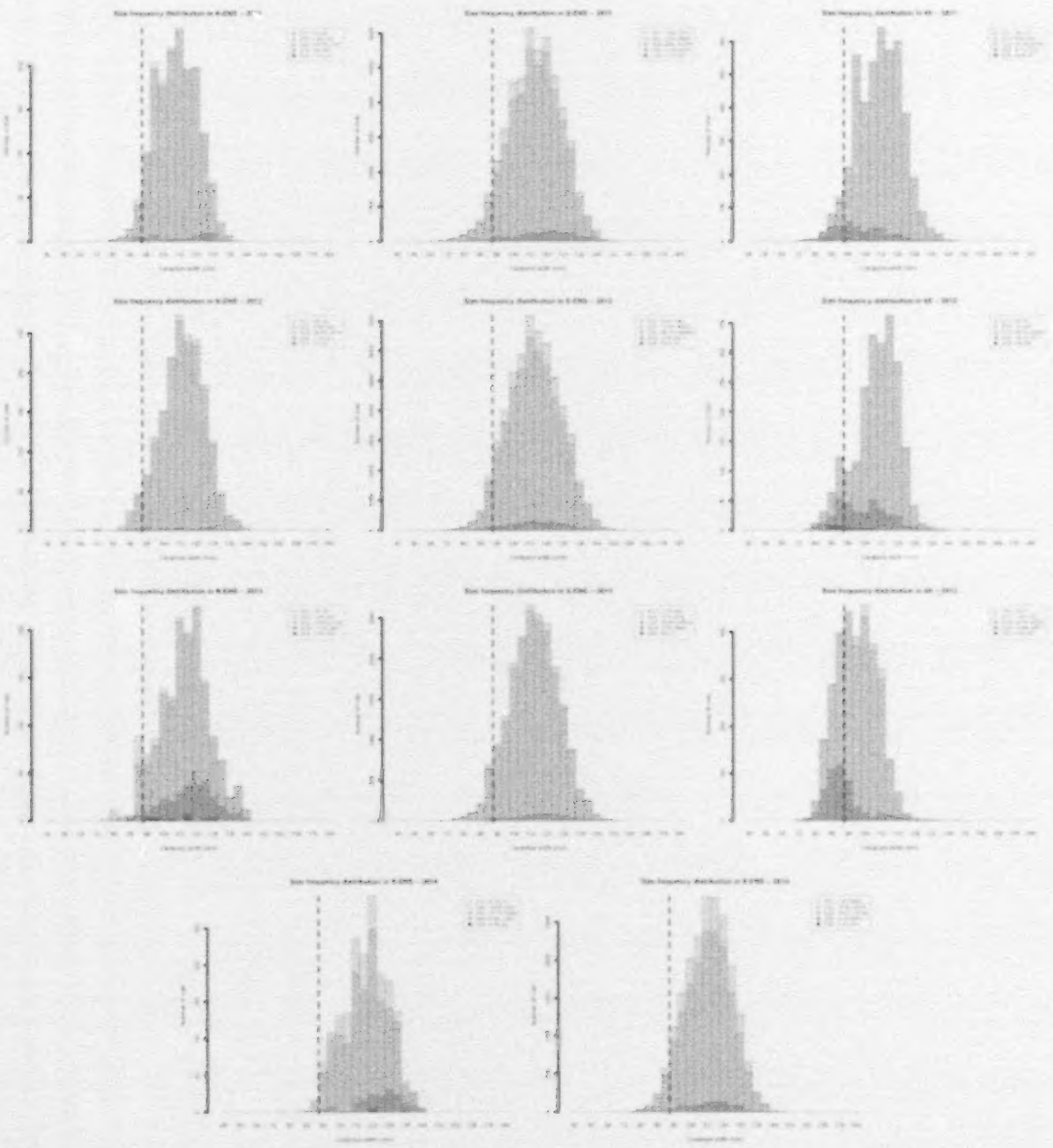


Figure 46: Snow crab size frequency distribution of all at-sea-observer monitored snow crab separated by carapace condition sampled during the 2010- 2013 fishing seasons. Vertical lines indicate 95 mm carapace width (CW).

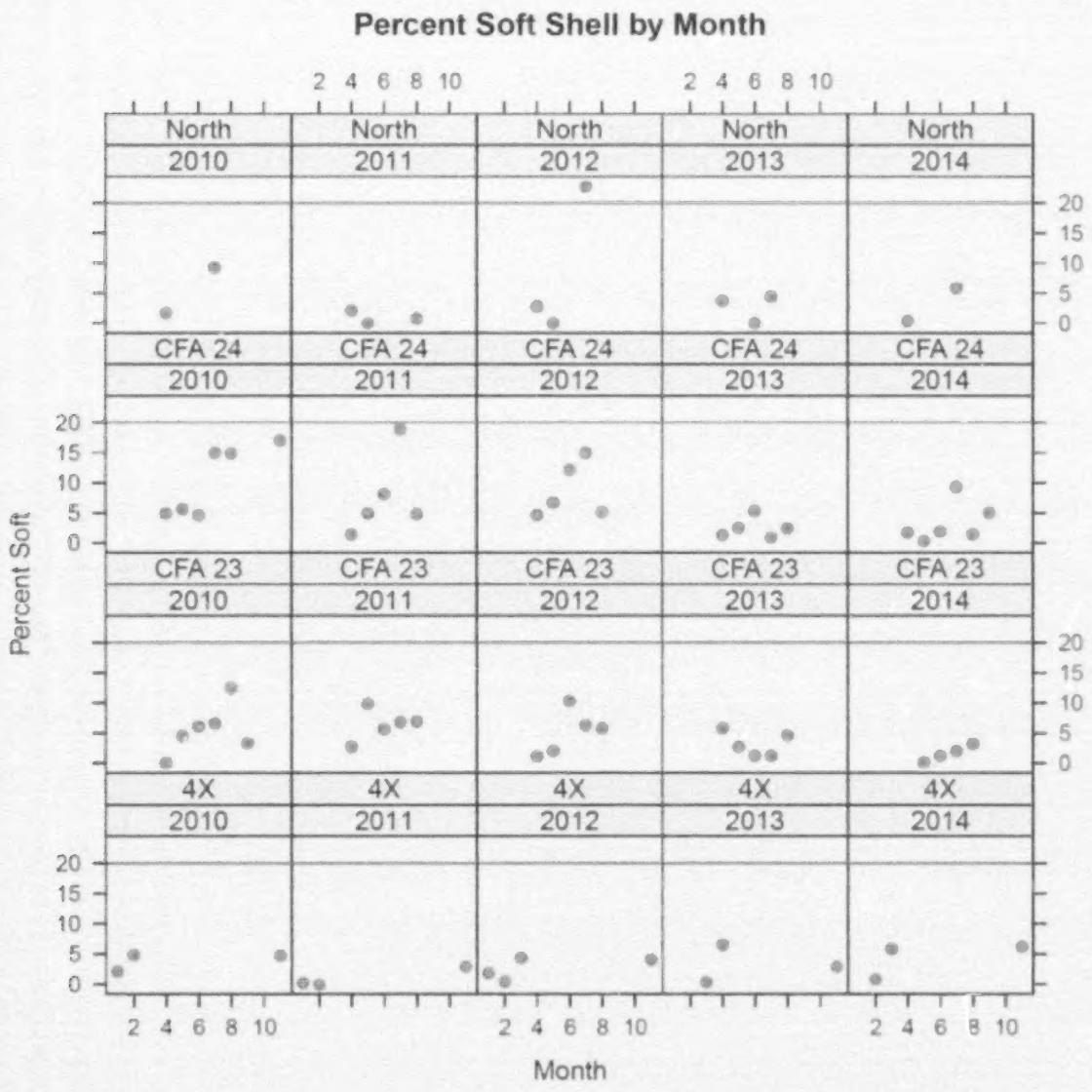


Figure 47: Occurrence of soft-shelled snow crab by month and crab fishing area sampled by at-sea observers from commercial crab traps during 2010-2014.

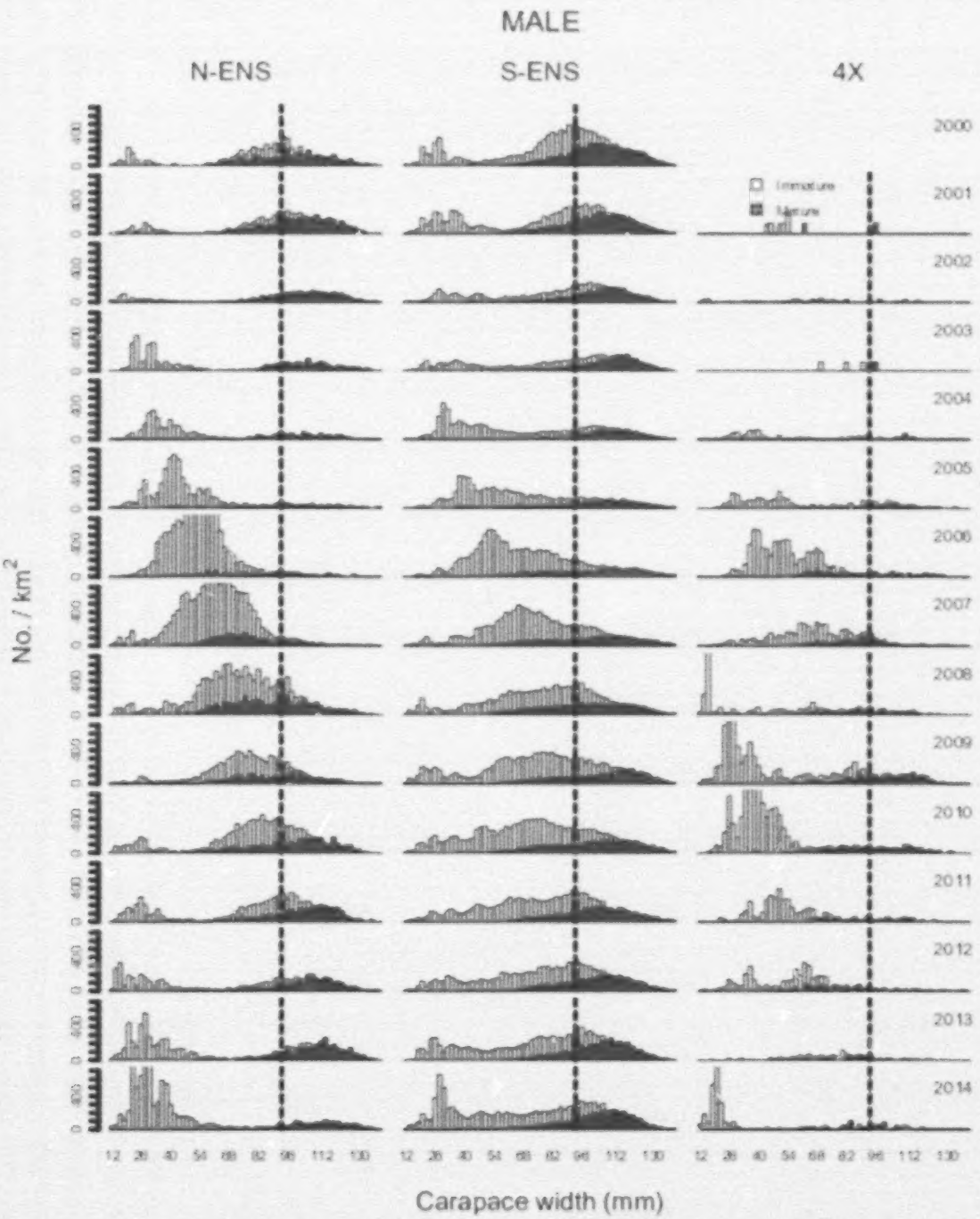


Figure 48: Size frequency histograms of carapace width (CW) of male snow crabs obtained from the snow crab survey between 2000 and 2014. Due to the expansion of the survey from core areas to the full extent of snow crab grounds, the areal densities of crab in S-ENS and 4X are only directly comparable from 2005 to present.

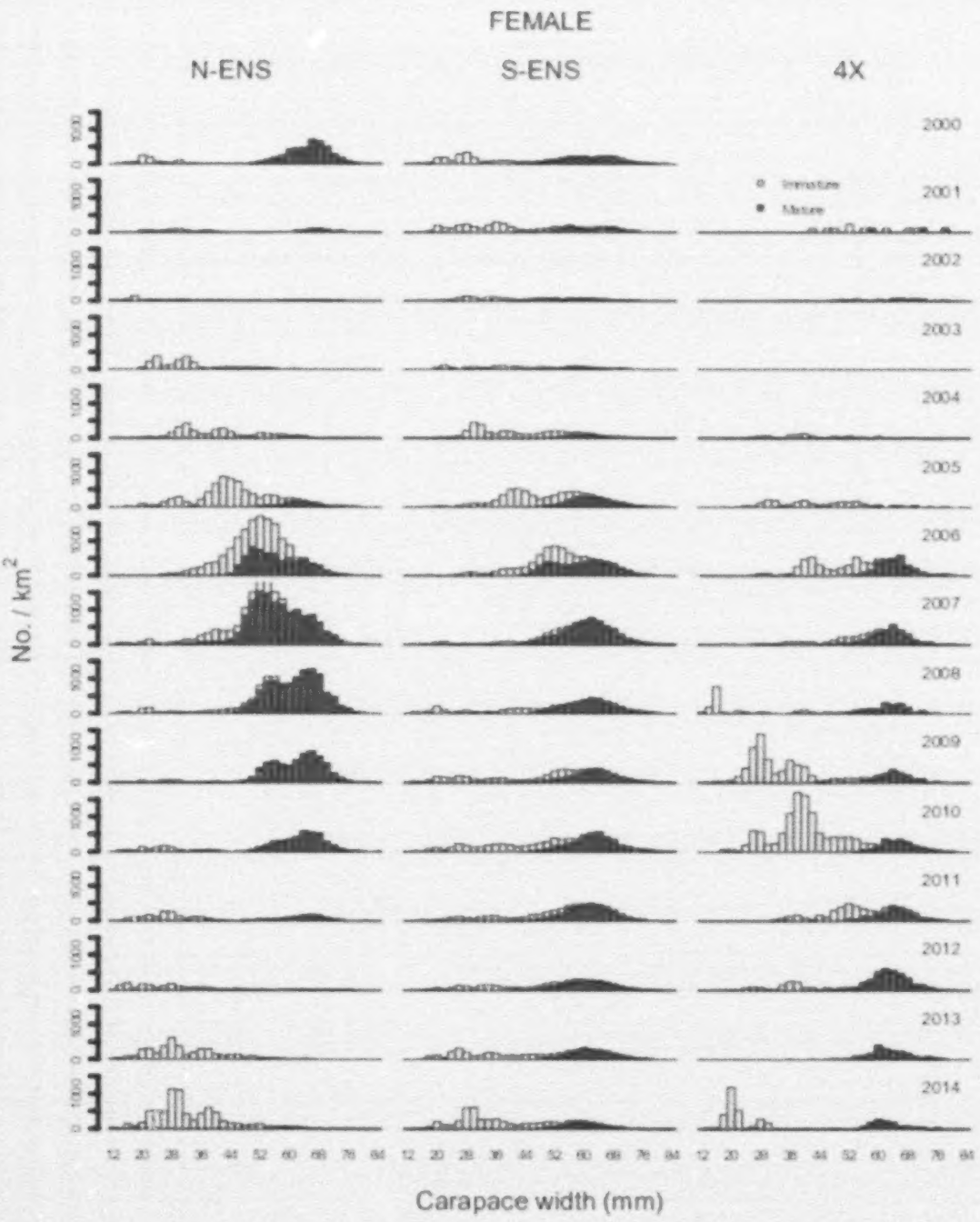


Figure 49: Size frequency histograms of carapace width (CW) of female snow crabs obtained from the snow crab survey between 2000 and 2014. Due to the expansion of the survey from core areas to the full extent of snow crab grounds, the areal densities of crab in S-ENS and 4X are only directly comparable from 2005 to present.

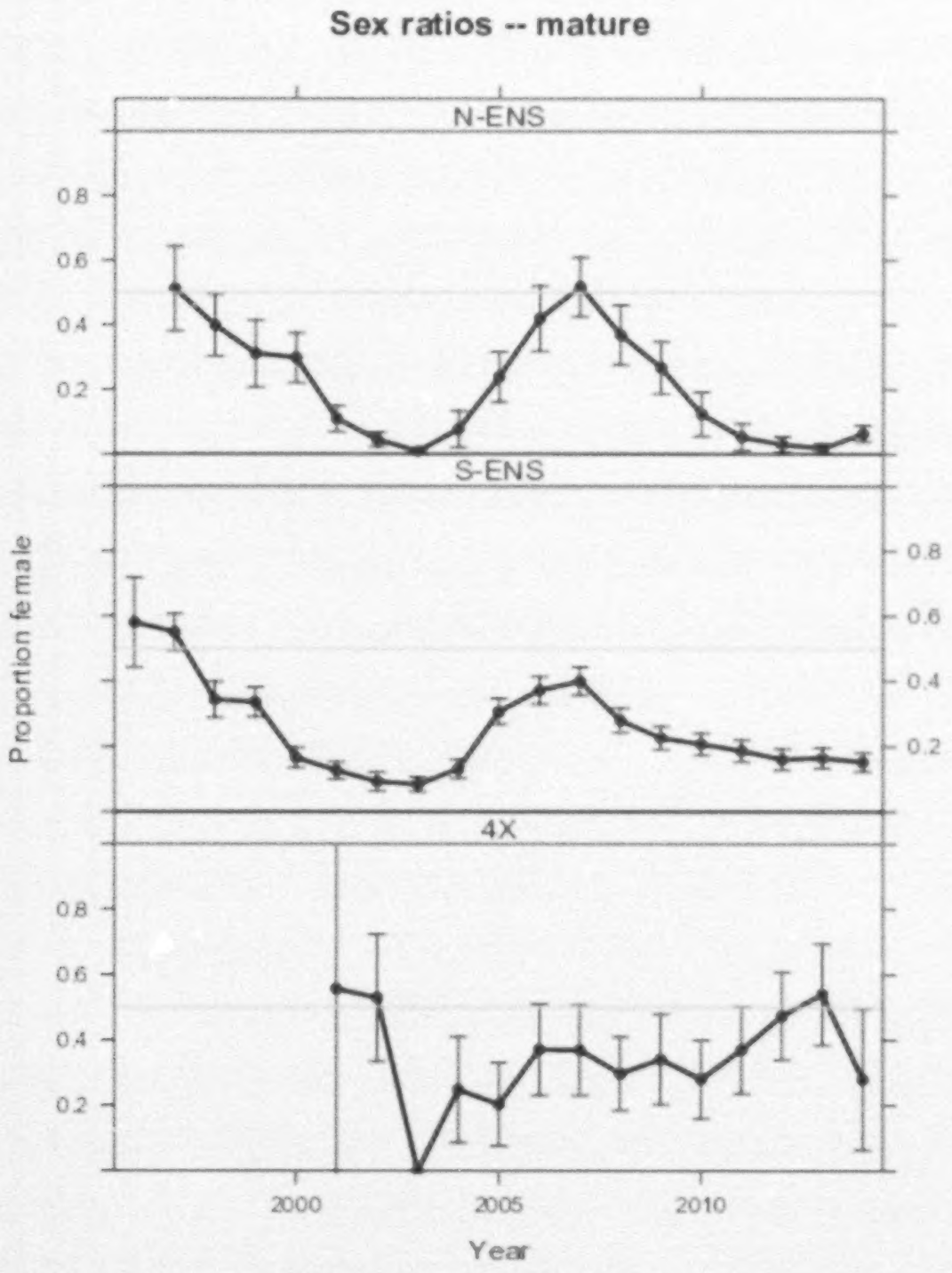


Figure 50: Annual sex ratios (proportion female) from the mature fraction of the snow crab observed during the snow crab survey between 1996 and 2014. One standard error bar is presented.

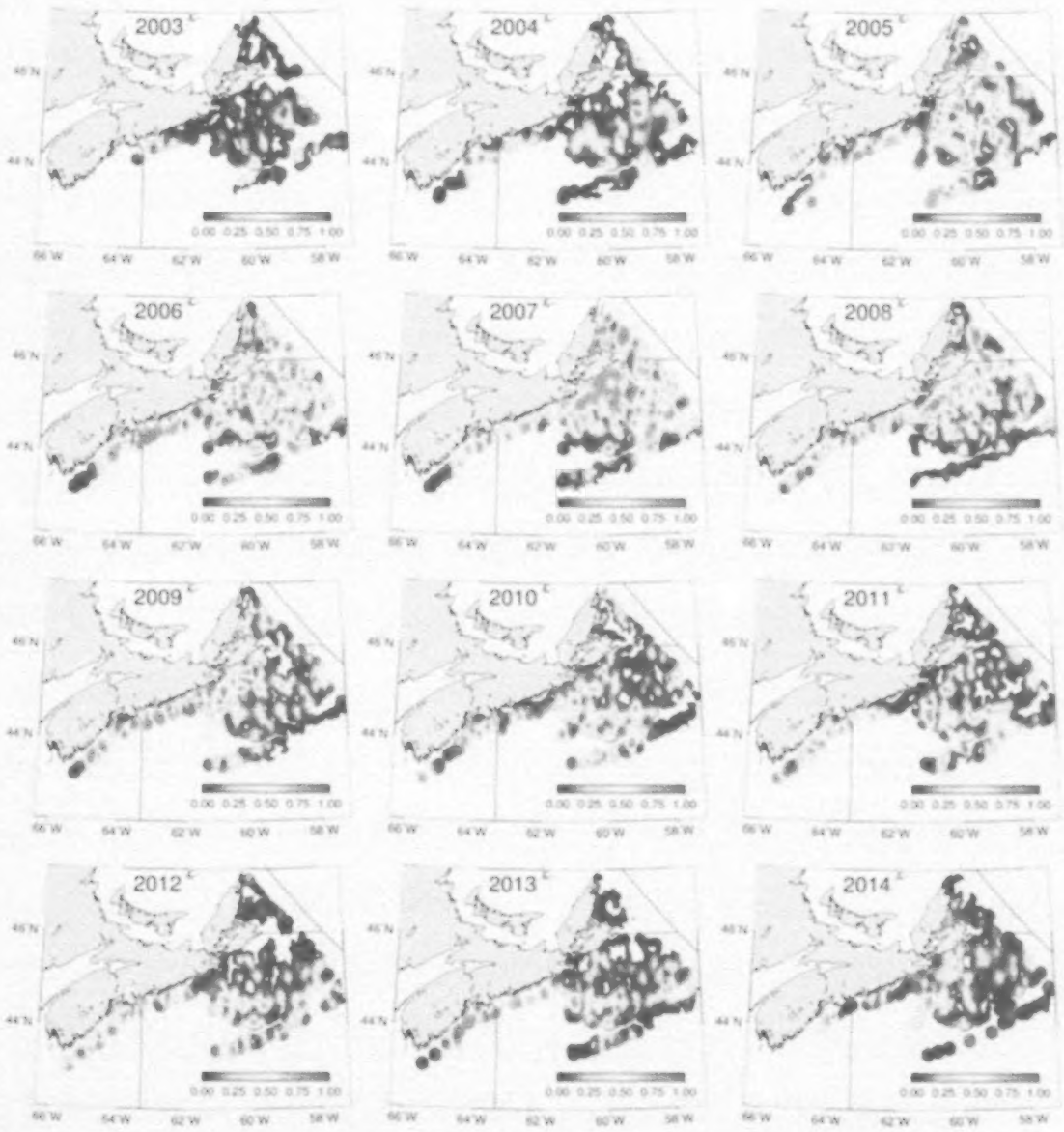


Figure 51: Maps of the distribution of morphometrically mature sex ratios (proportion female) of snow crab on the Scotian Shelf from 2003-2014.

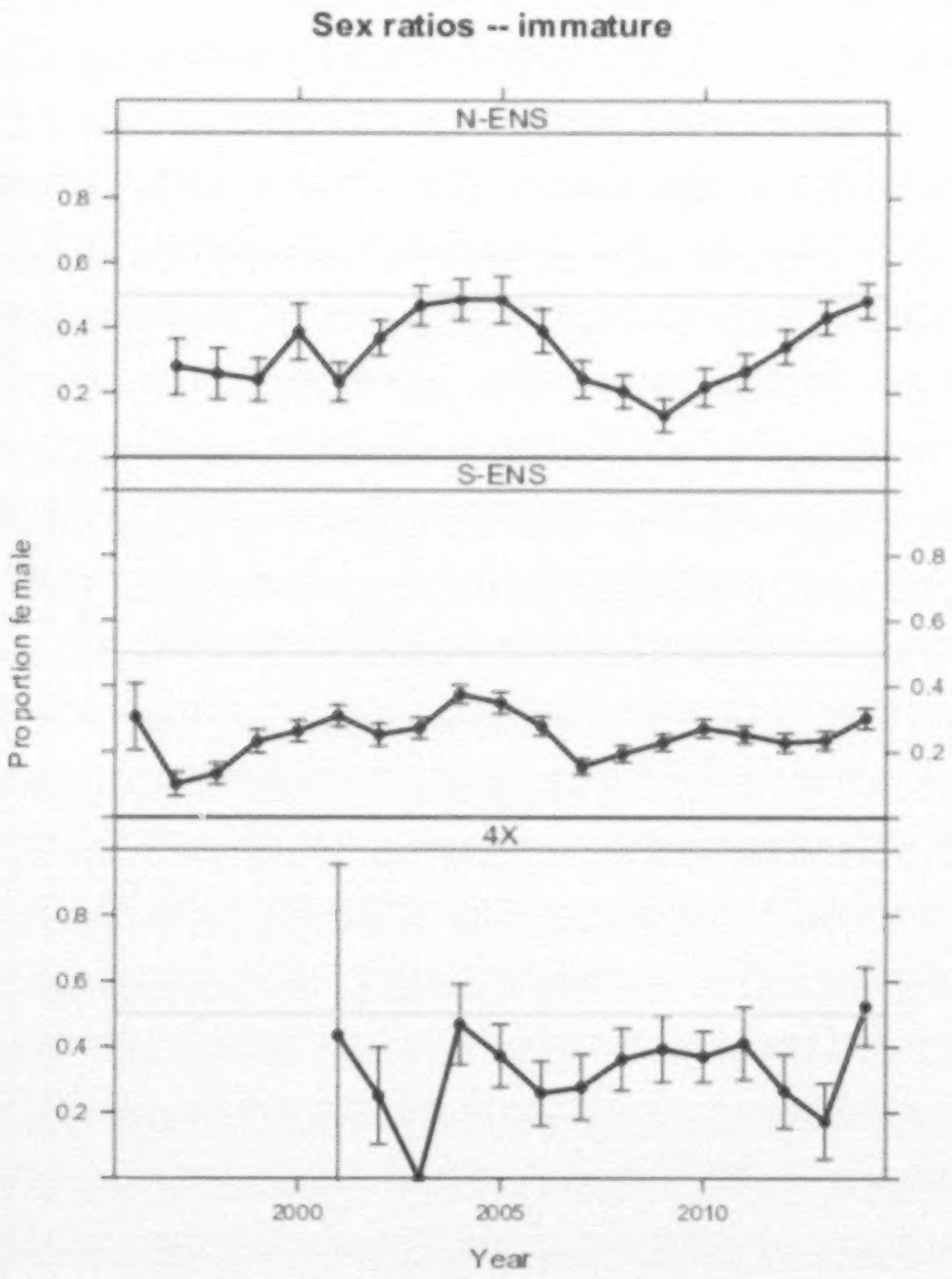


Figure 52: Annual sex ratios (proportion female) of immature snow crab on the Scotian Shelf from 1996-2014. One standard error bar is presented.

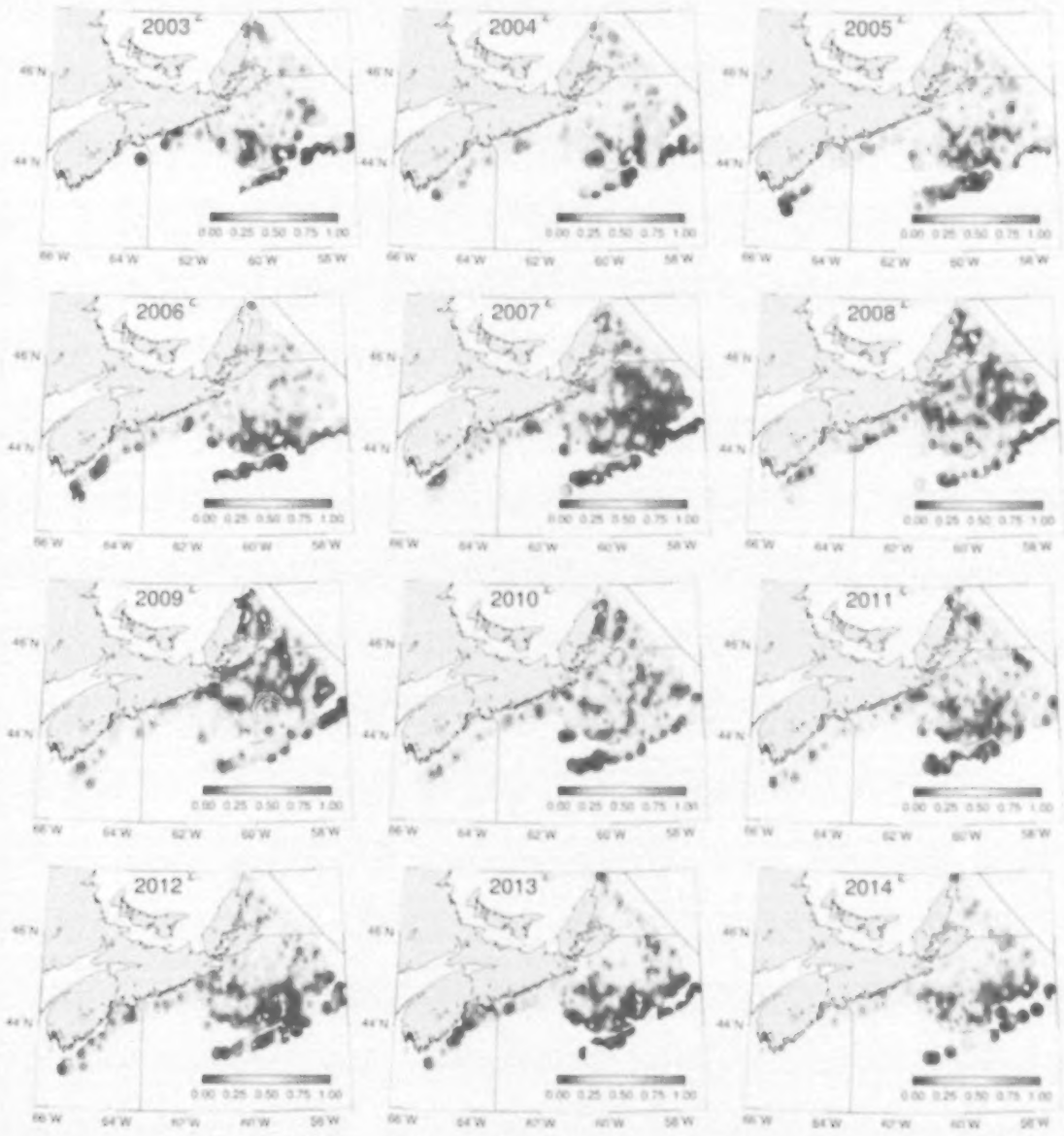


Figure 53: Maps of the distribution of morphometrically immature sex ratios (proportion female) of snow crab on the Scotian Shelf from 2003-2014.

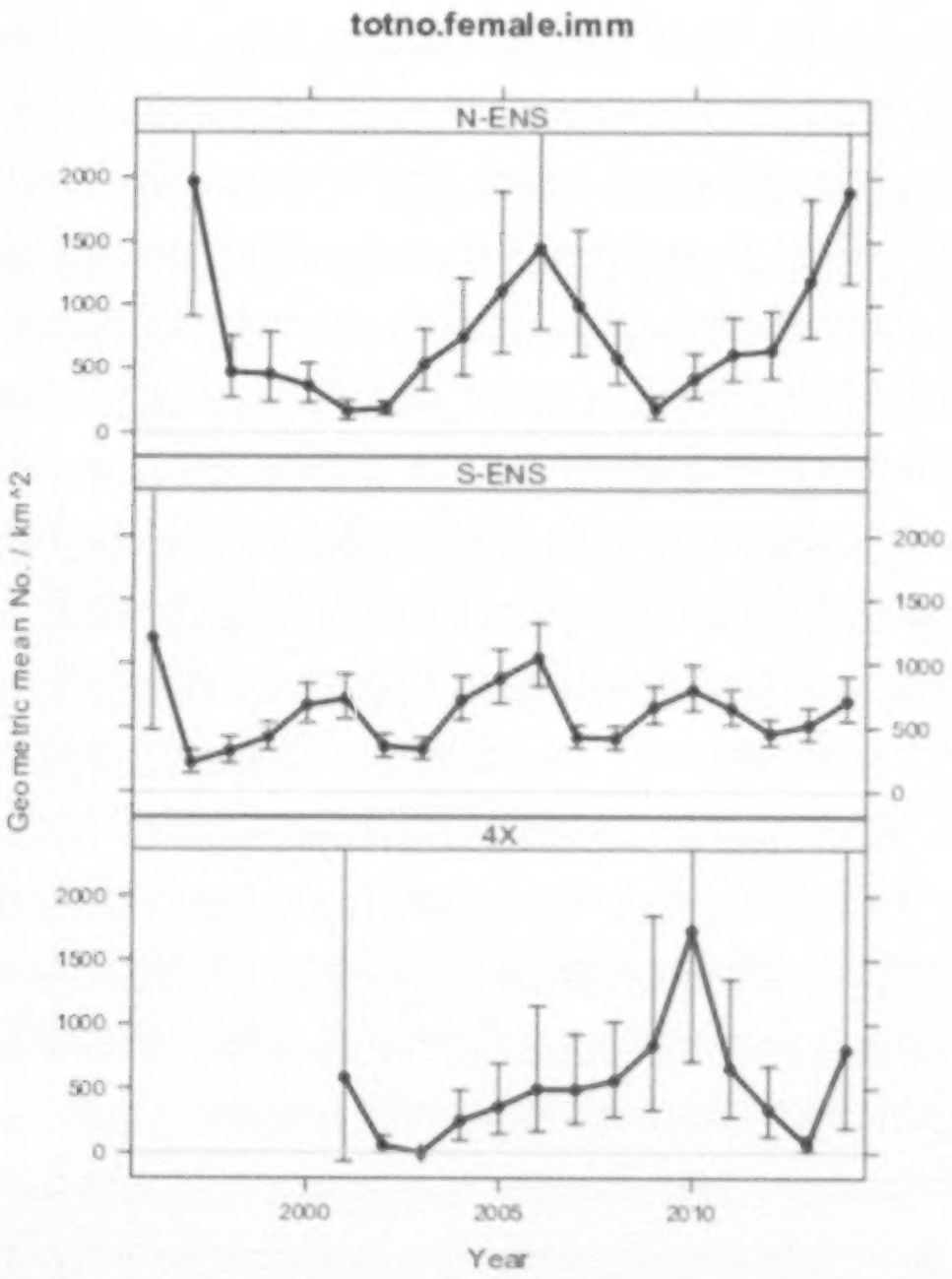


Figure 54: Time series of numeric densities of immature female snow crab on the Scotian Shelf.

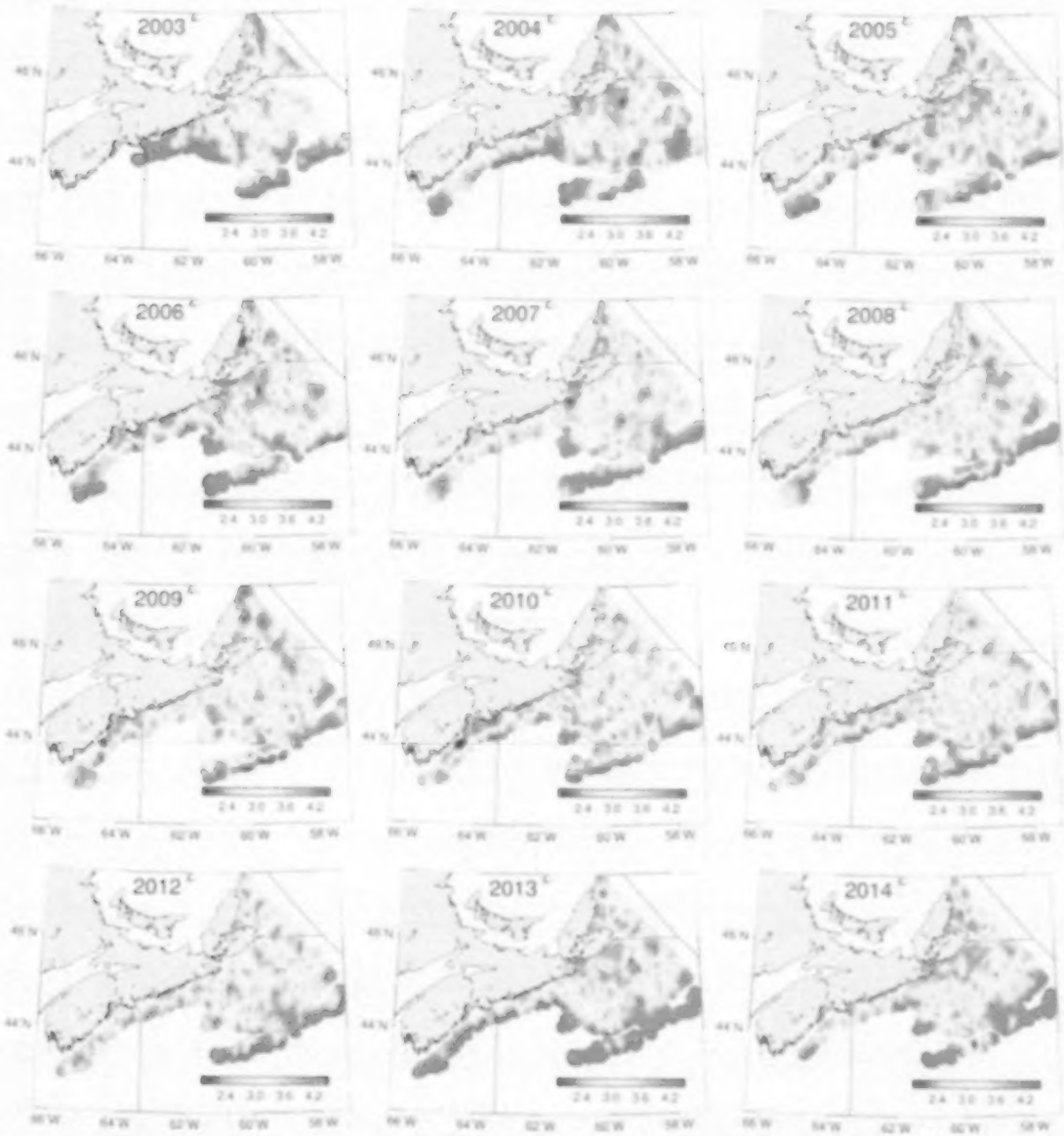


Figure 55: Maps of the numerical densities of the immature female snow crabs on the Scotian Shelf from 2003-2014. Scale in log(n/km^2).

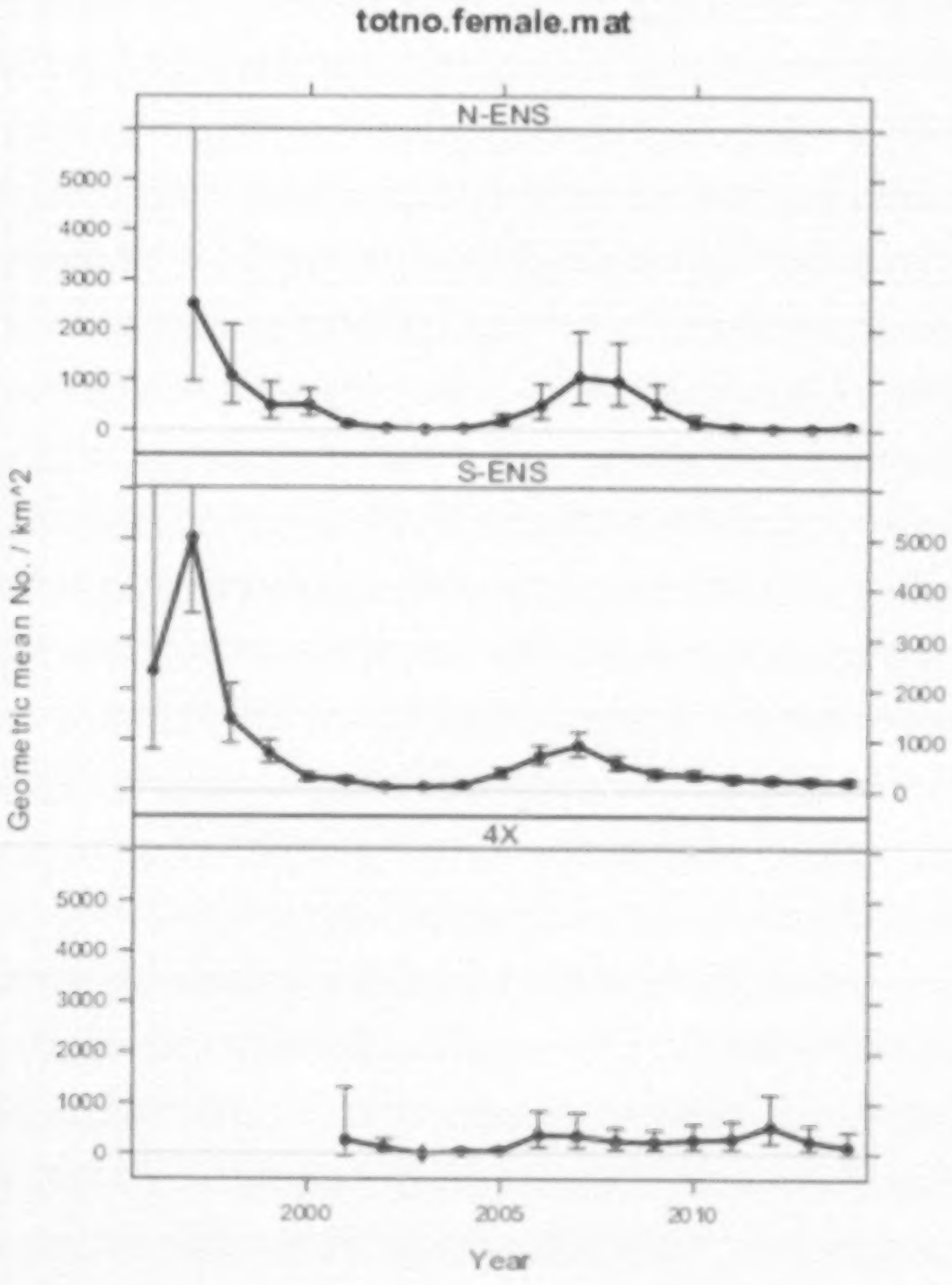


Figure 56: Time series of numeric densities of mature female snow crab in the Scotian Shelf.

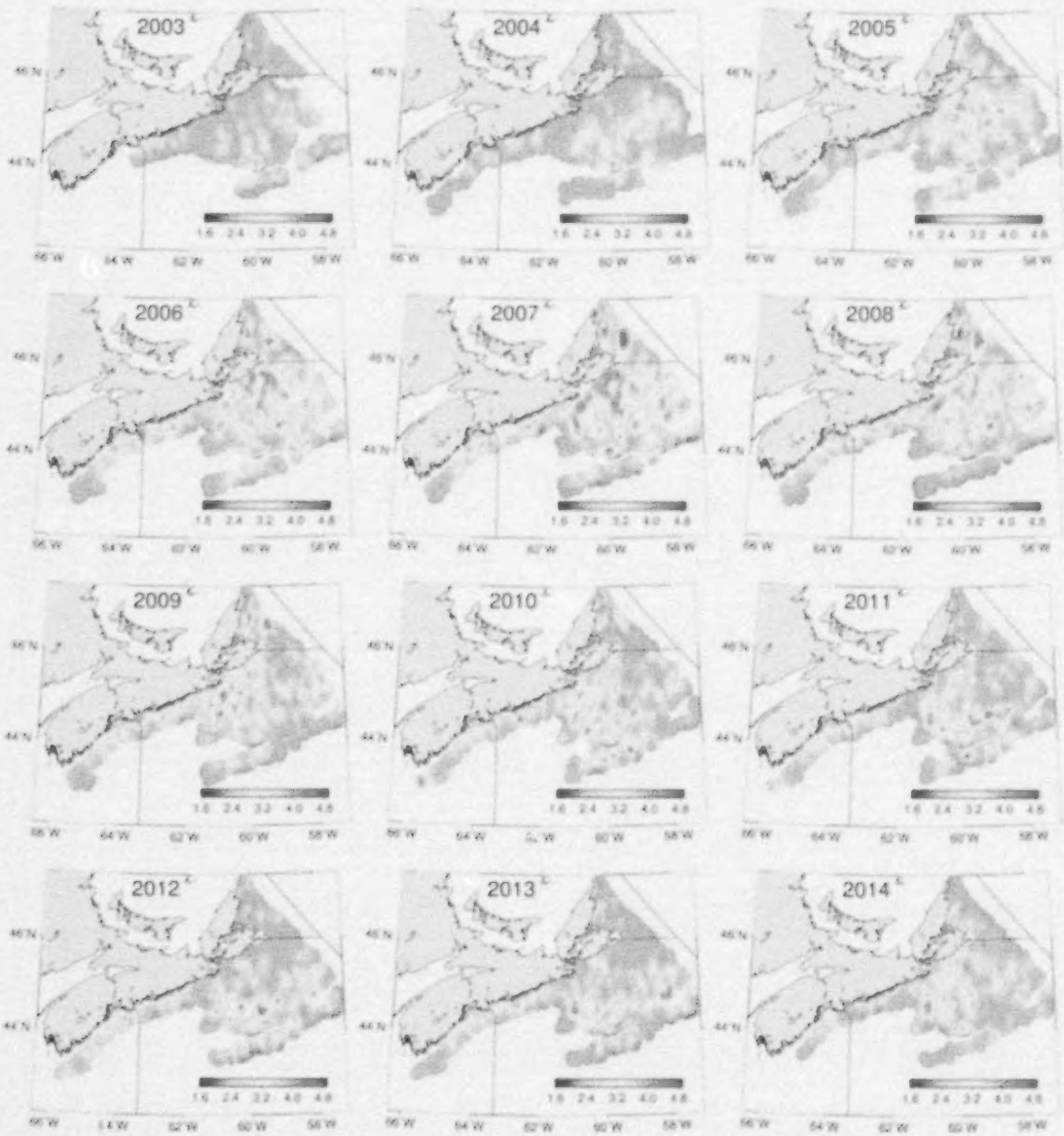


Figure 57: Maps of the numeric densities of the mature female snow crab on the Scotian Shelf between 2003 and 2014. Scale in log(n/km^2).

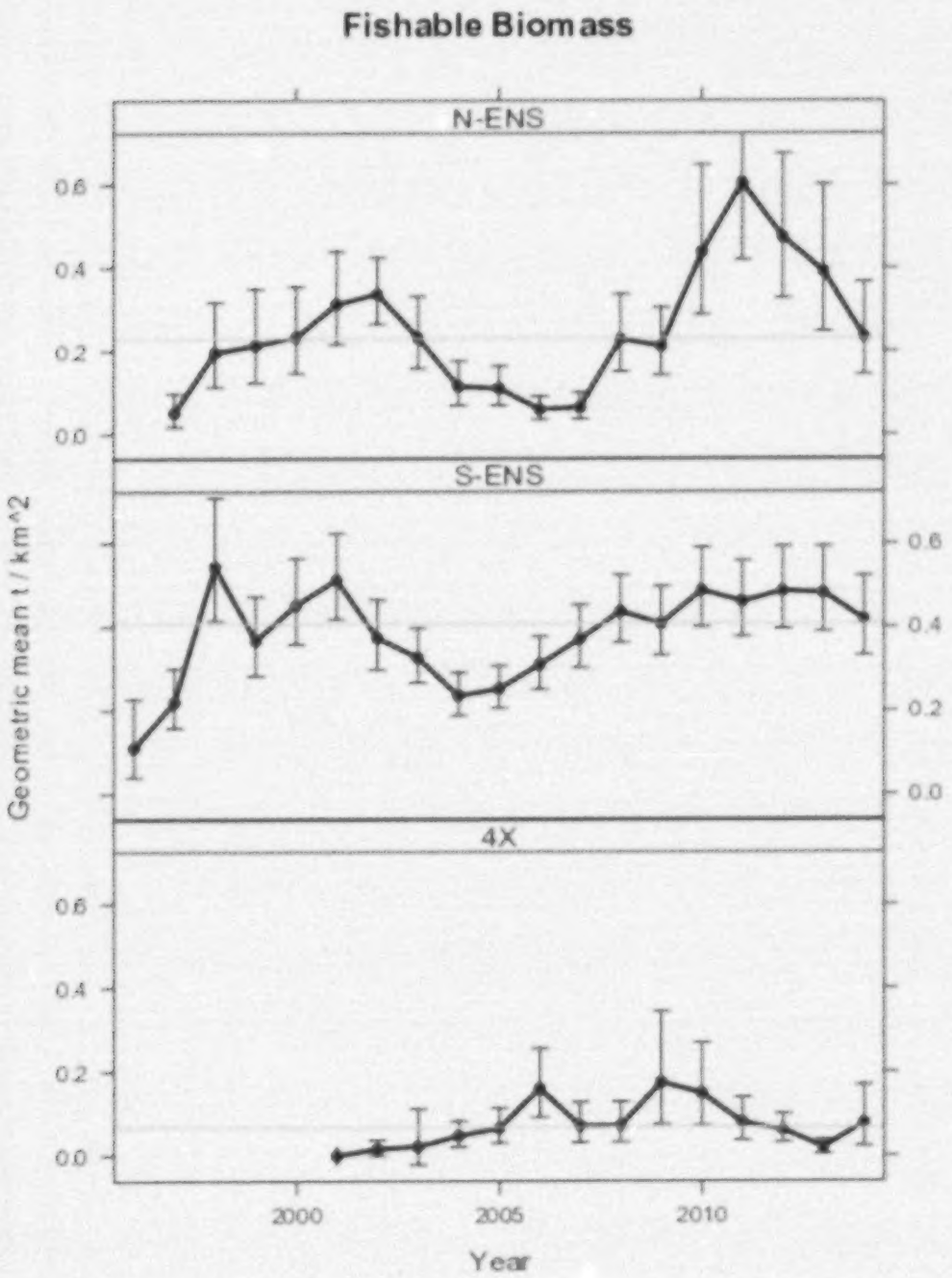


Figure 58: Time series trends in the geometric mean fishable biomass obtained from the annual snow crab survey. Error barrs are 95% confidence intervals.

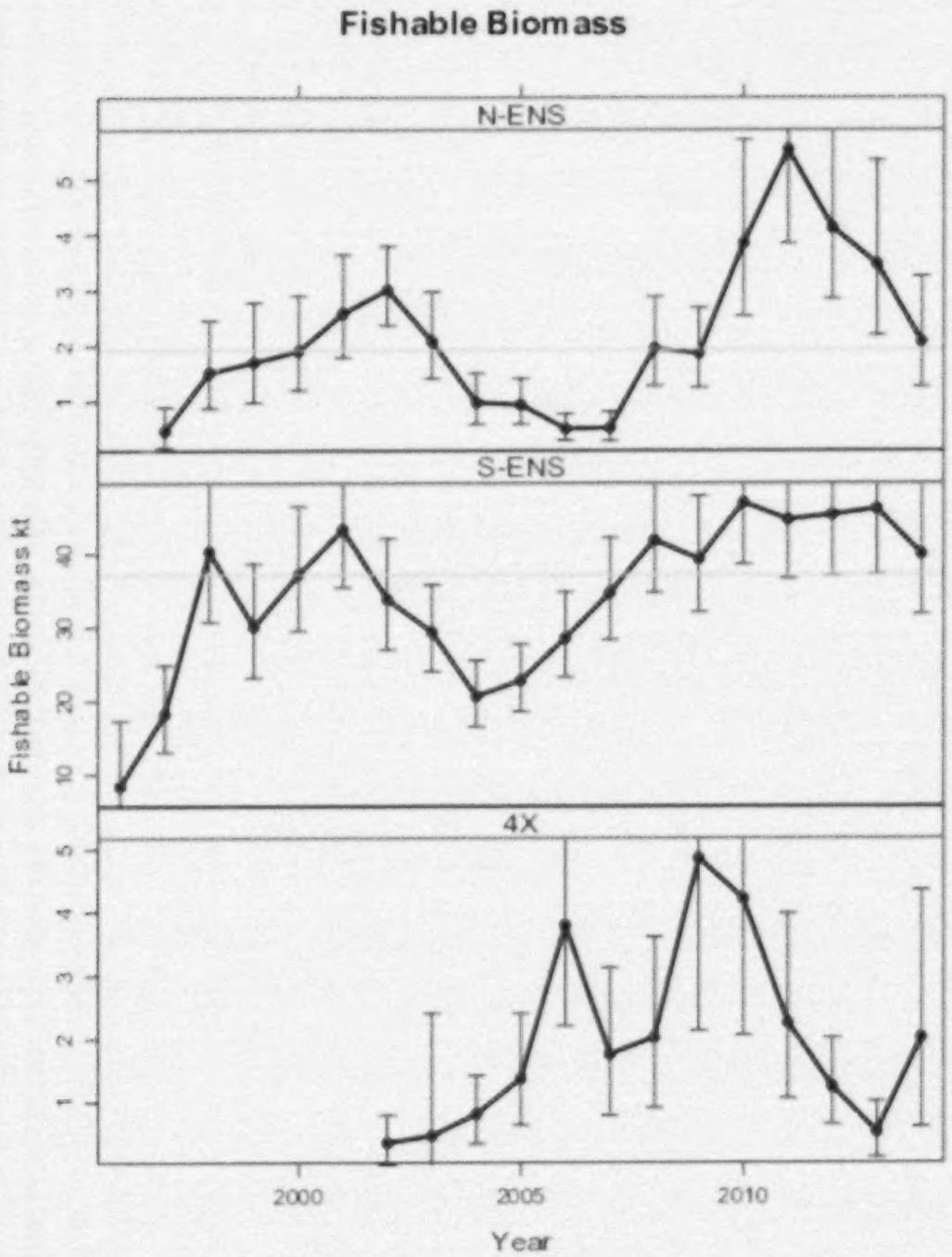


Figure 59: Time series trends in the area expanded geometric mean fishable biomass obtained from the annual snow crab survey. Error bars are 95% confidence intervals.

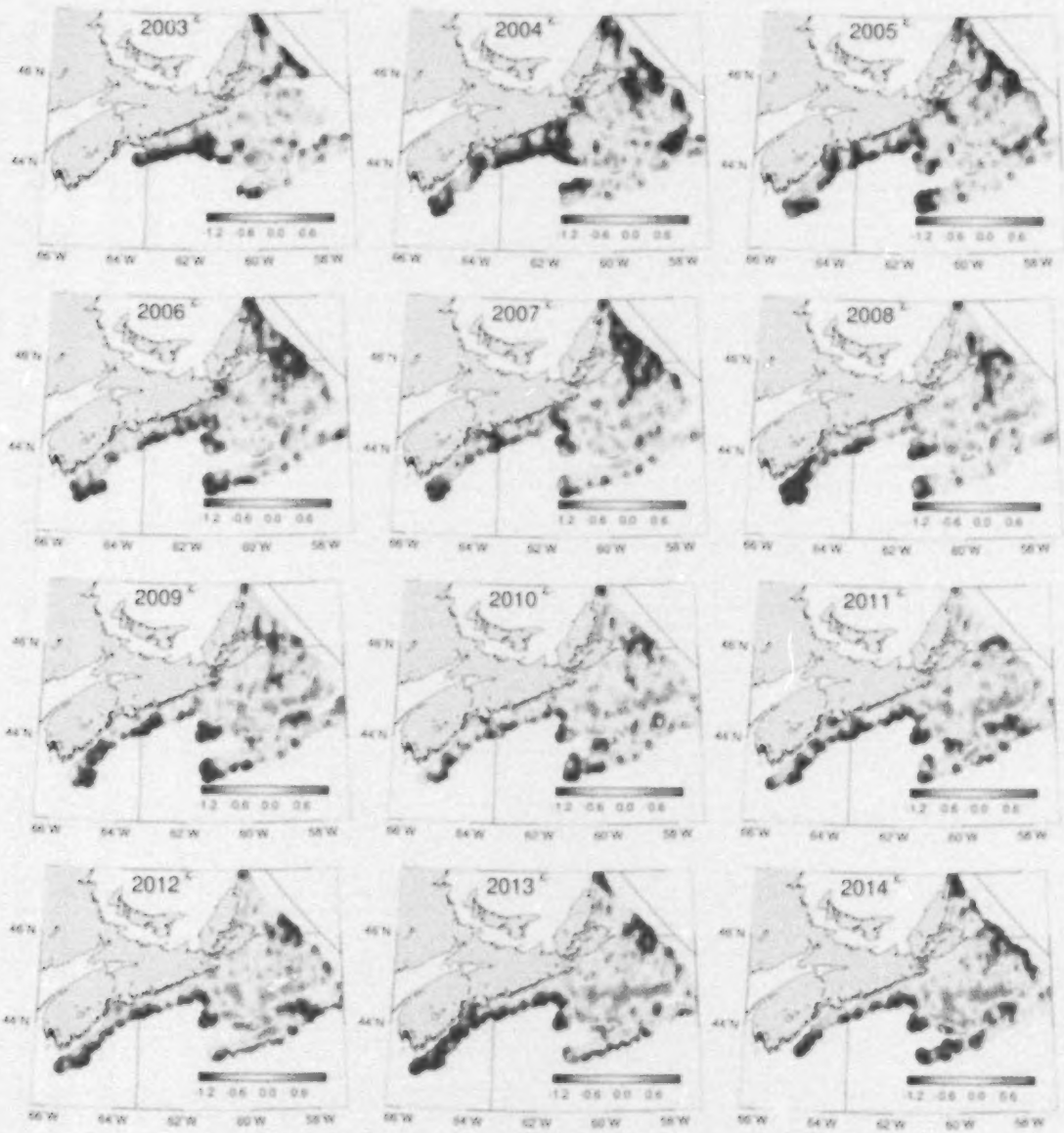


Figure 60: Maps of the fishable biomass densities of snow crab on the Scotian Shelf. Scale is log(t/km^2).

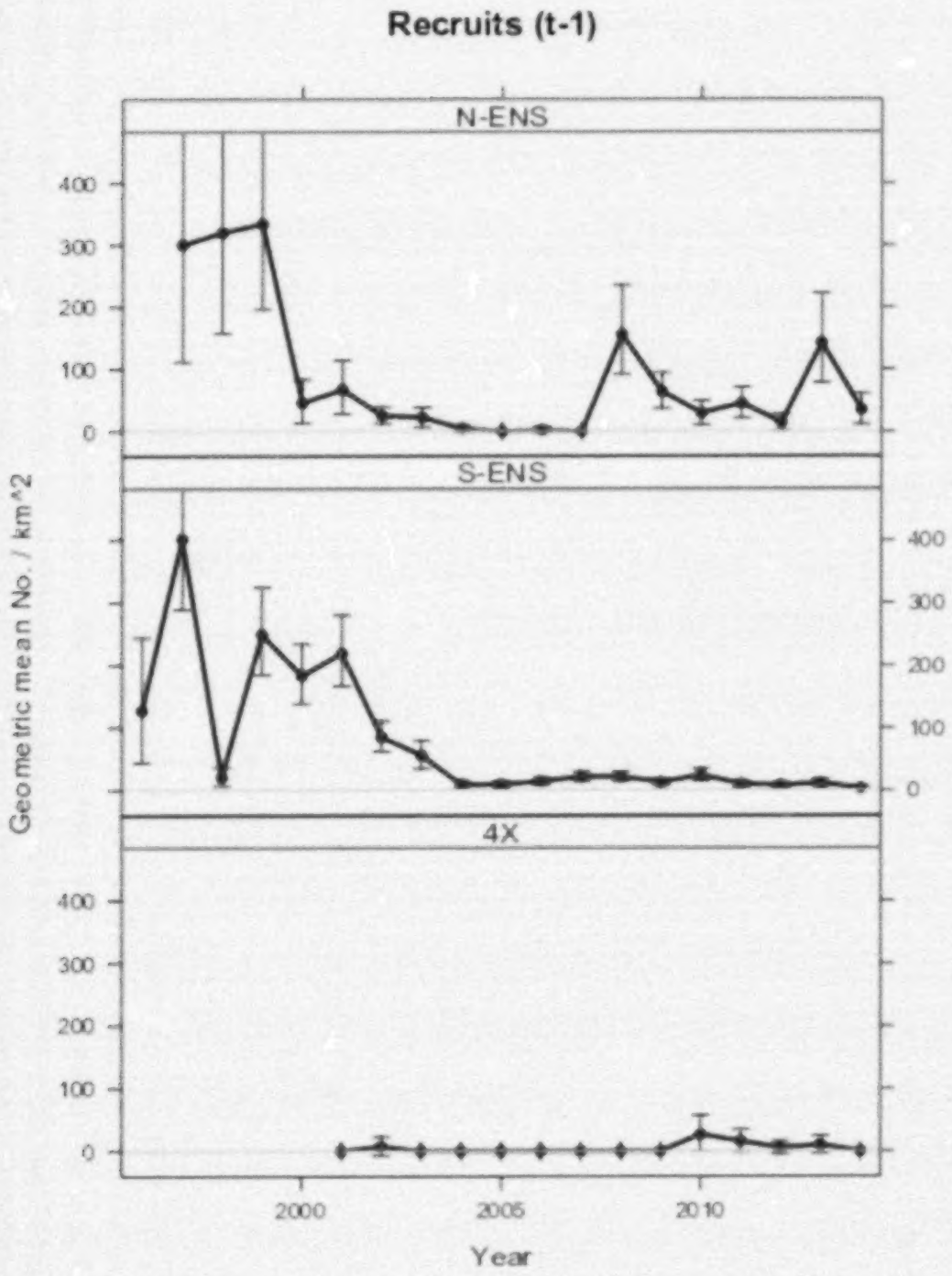


Figure 61: Time series trends in the geometric mean recruiting male abundance obtained from the annual snow crab survey. Error bars are 95% confidence intervals about the geometric mean.

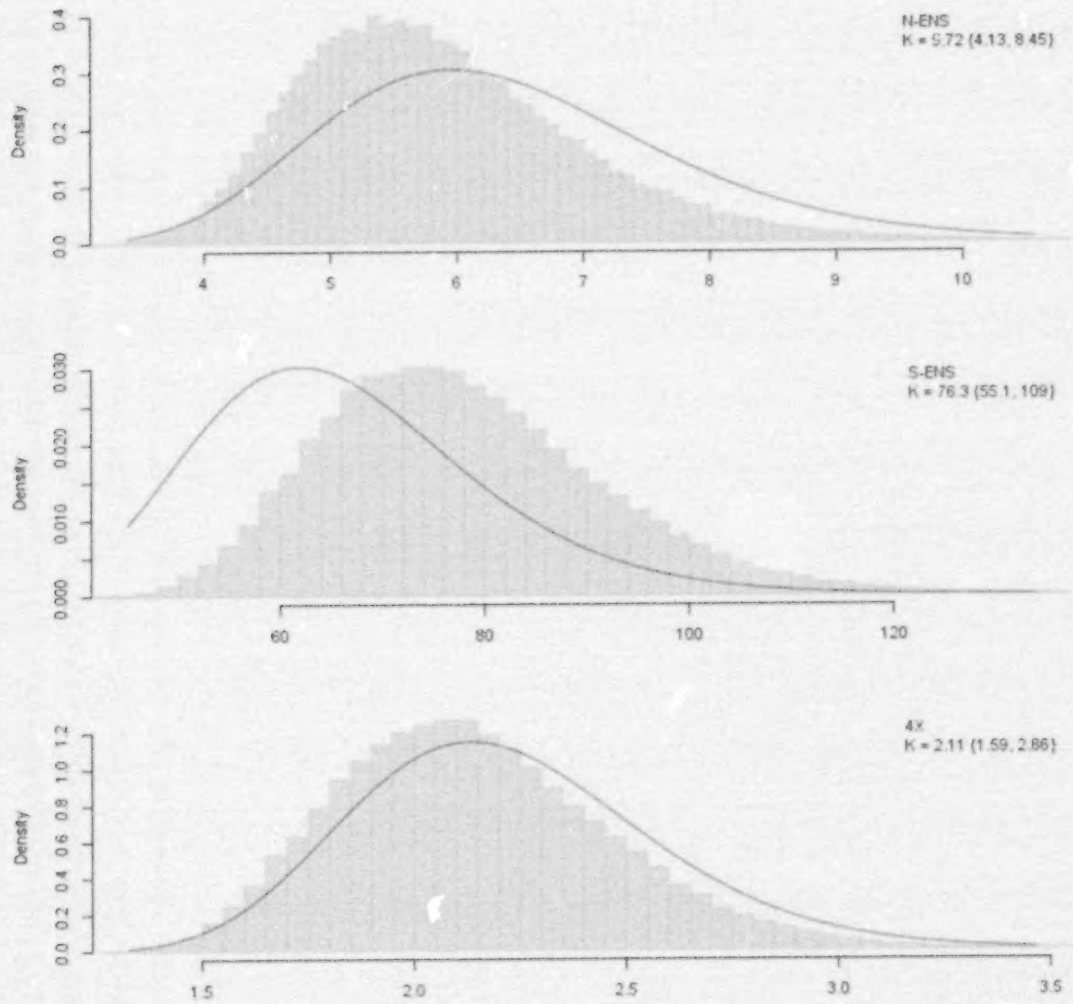


Figure 62: Prior (red lines) and posterior (bars) distributions for carrying capacity, K, from the biomass dynamic model of snow crab production in snow crab fishing areas on the Scotian Shelf. Within each panel, estimates of posterior median and 95% credible intervals are given in the legend.

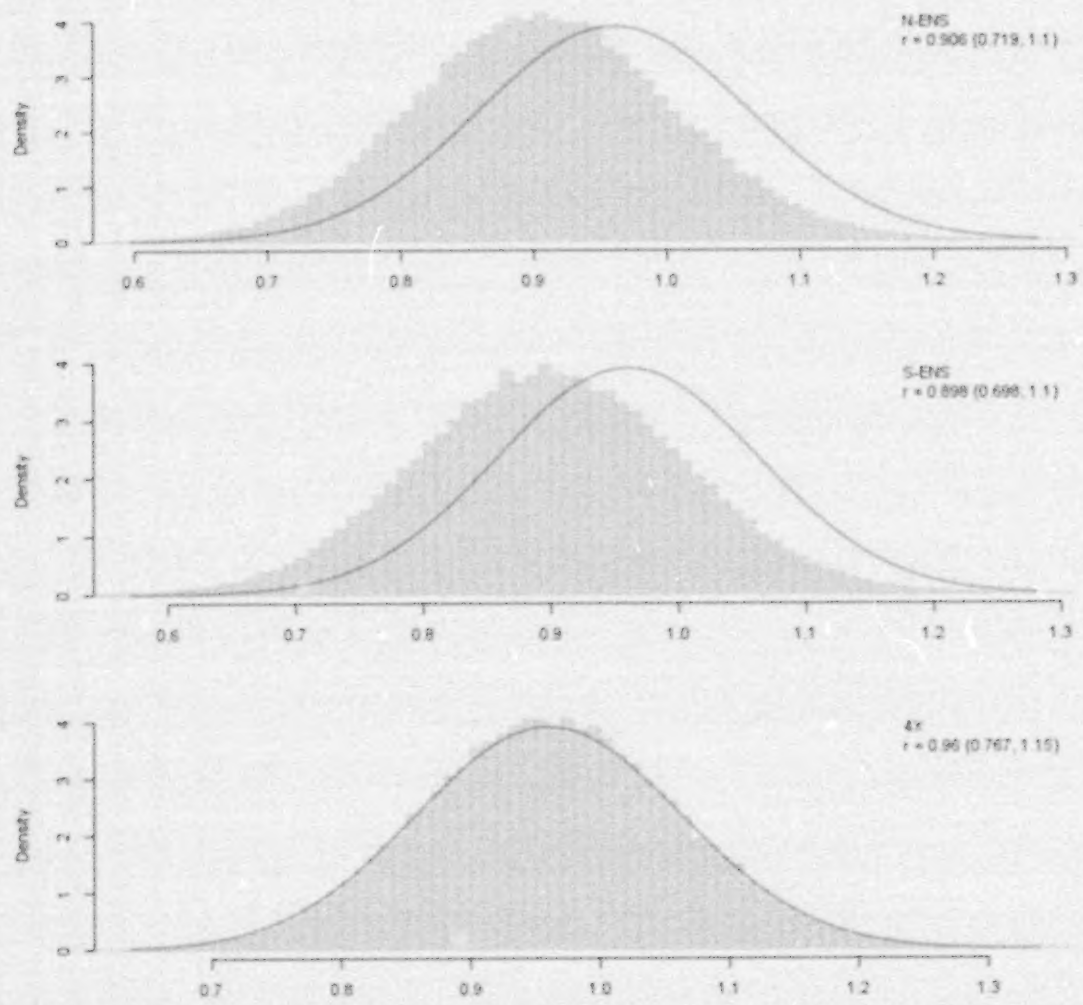


Figure 63: Prior (red lines) and posterior (bars) distributions for population growth rate parameter, r, from the biomass dynamic model of snow crab production in snow crab fishing areas on the Scotian Shelf. Within each panel, estimates of posterior median and 95% credible intervals are given in the legend.

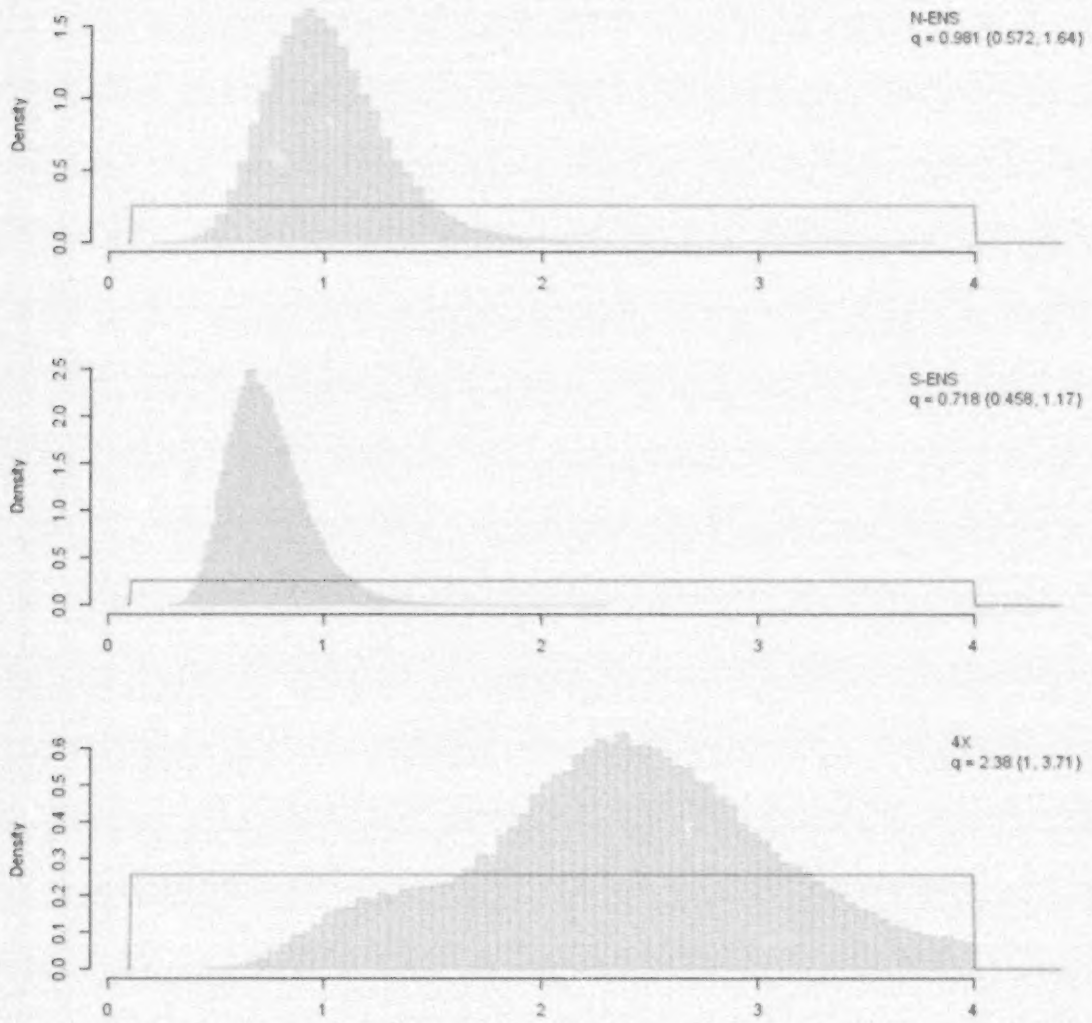


Figure 64: Prior (red lines) and posterior (bars) distributions for catchability, q, from the biomass dynamic model of snow crab production in snow crab fishing areas on the Scotian Shelf. Within each panel, estimates of posterior median and 95% credible intervals are given in the legend.

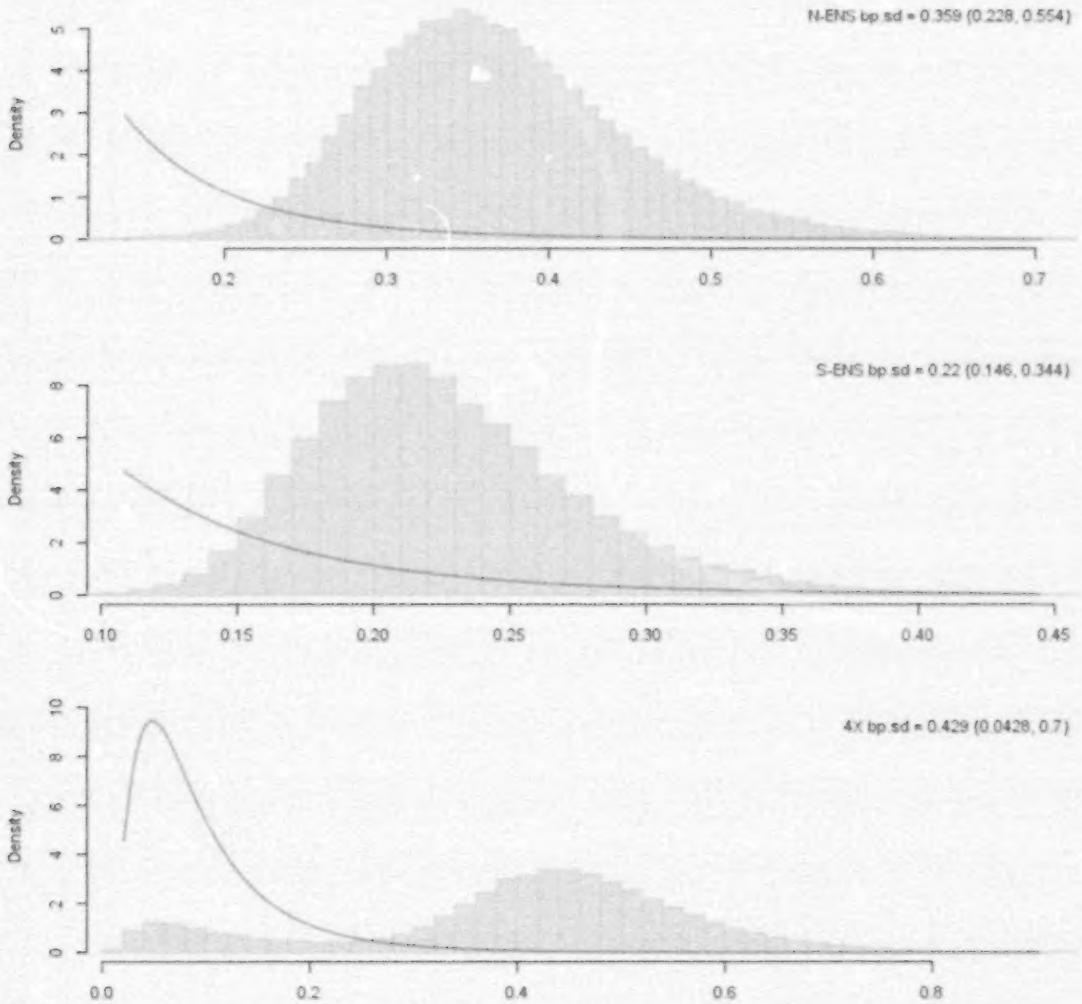


Figure 65: Prior (red lines) and posterior (bars) distributions for process error from the biomass dynamic model of snow crab production in snow crab fishing areas on the Scotian Shelf. Within each panel, estimates of posterior median and 95% credible intervals are given in the legend.

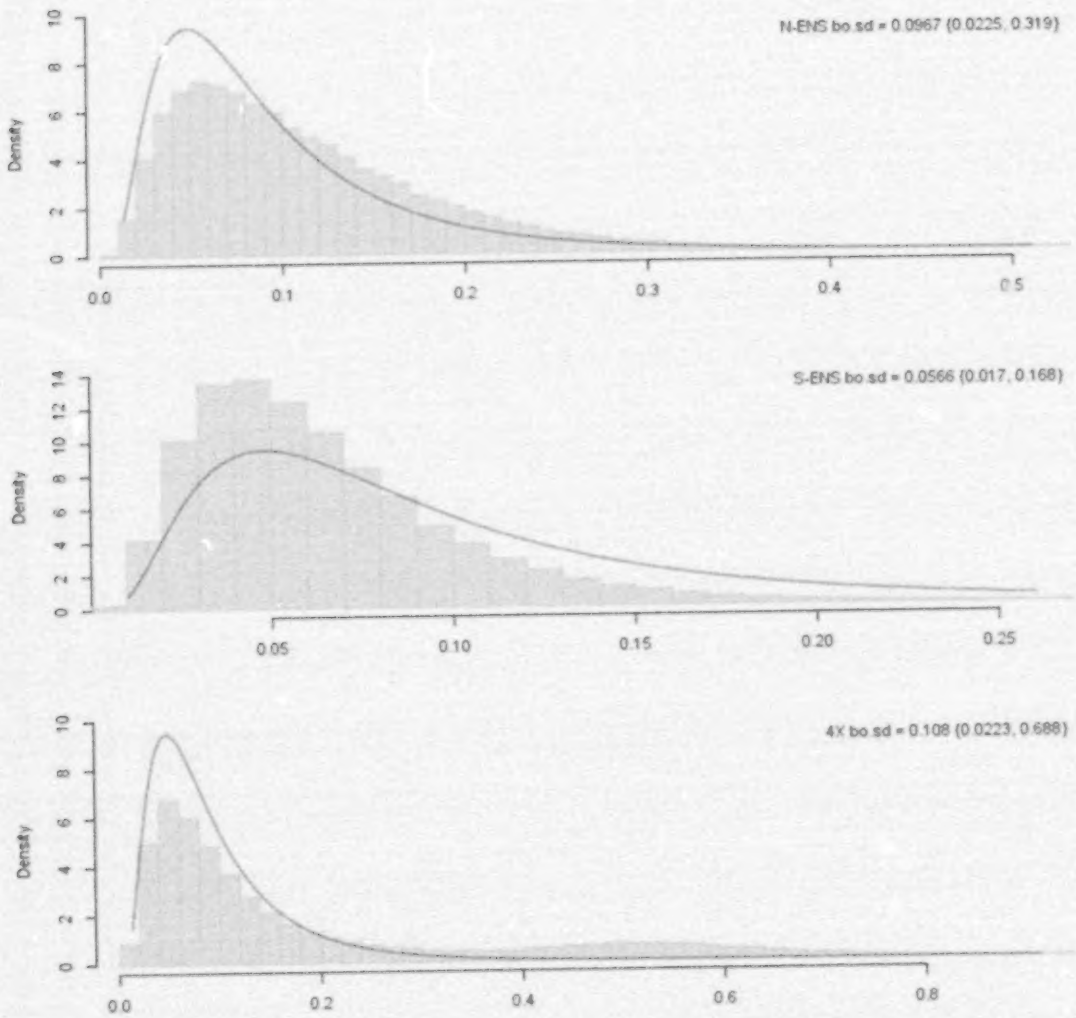


Figure 66: Prior (red lines) and posterior (bars) distributions for observation error from the biomass dynamic model of snow crab production in snow crab fishing areas on the Scotian Shelf. Within each panel, estimates of posterior median and 95% credible intervals are given in the legend.

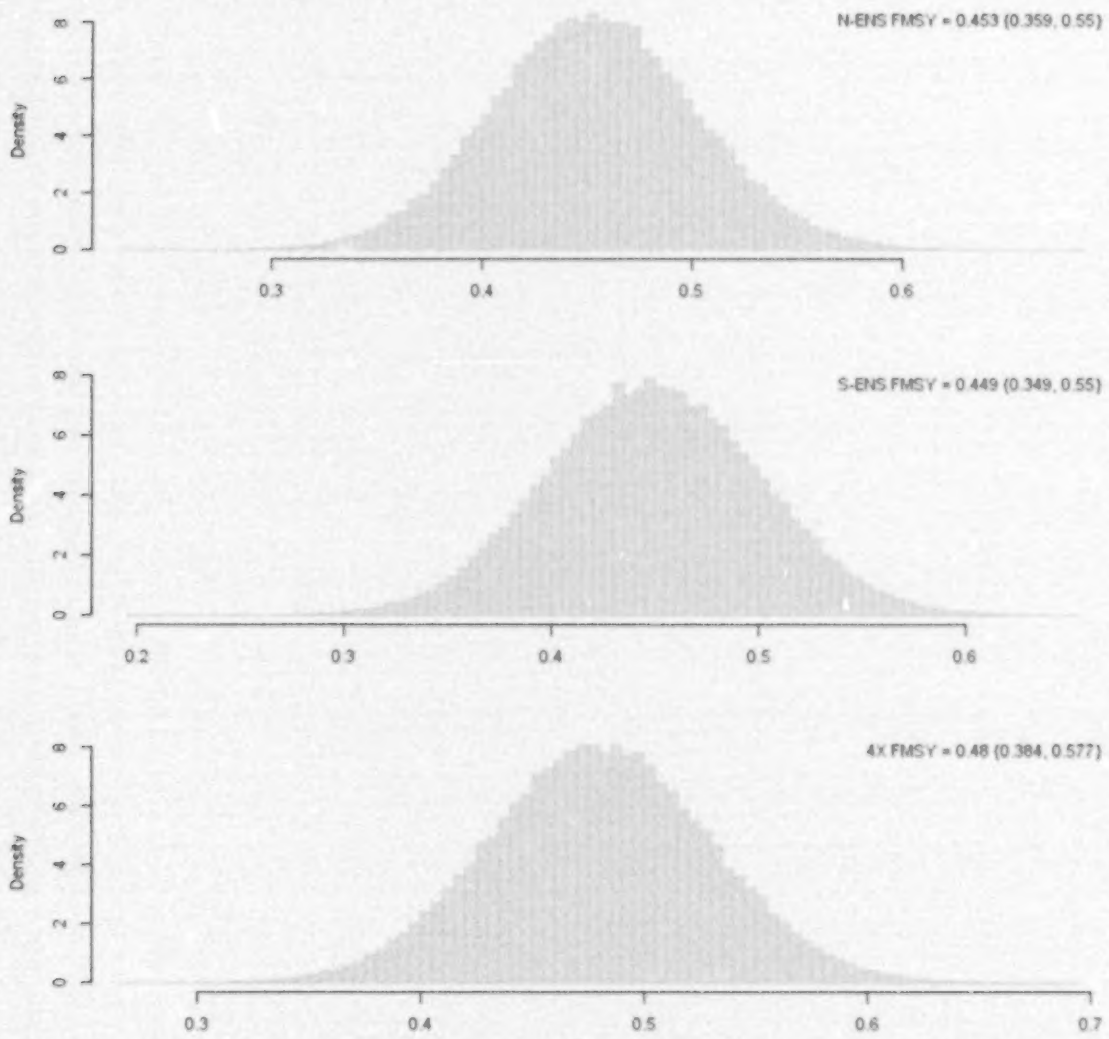


Figure 67: Posterior distribution for fishing mortality at maximum sustainable yield from the biomass dynamic model of snow crab production in snow crab fishing areas on the Scotian Shelf. Within each panel, estimates of posterior median and 95% credible intervals are given in the legend.

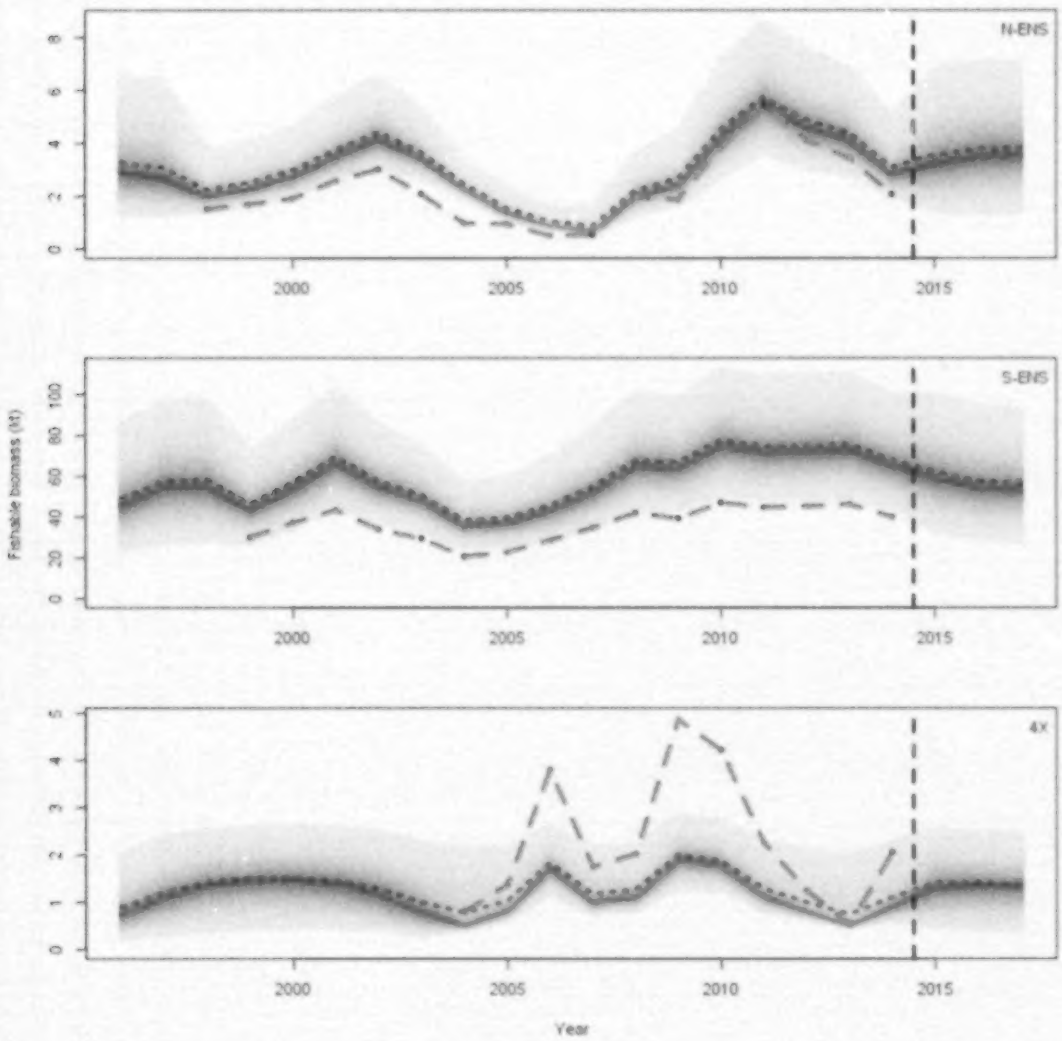


Figure 68: Time series of fishable biomass from the logistic population models. The fishable biomass index from the survey is shown in red dashed lines. The posterior mean fishable biomass estimate is shown as the blue stippled lines. The density distribution of posterior fishable biomass estimates are presented in greyscale with the darkest area being the medians and lightest representing the 95% credible intervals. A three year projection assuming an annual exploitation rate of 20% is also provided.

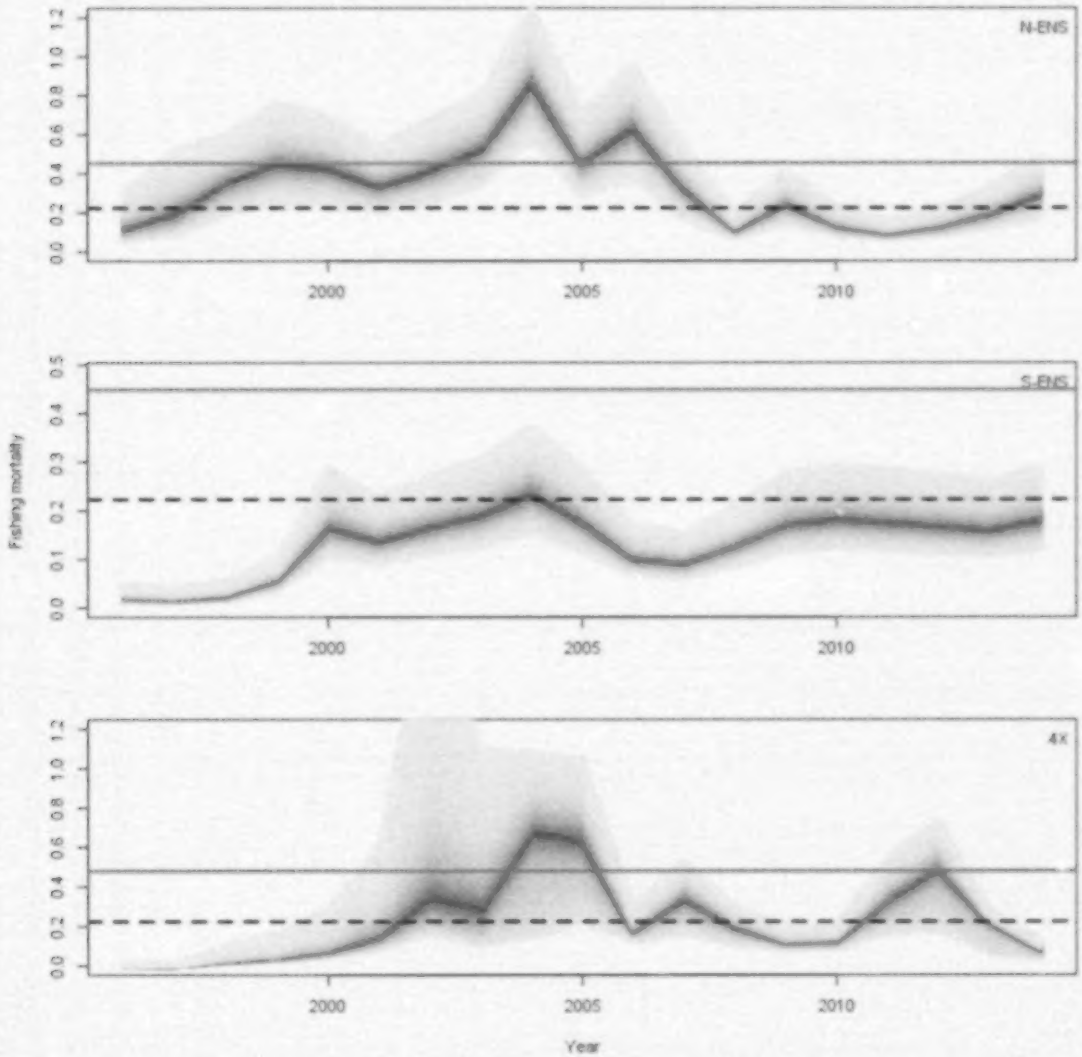


Figure 69: Time series of fishing mortality from the logistic production models for each area of the Scotian Shelf snow crab fishery. Posterior density distributions are presented in grey, with the darkest line being the median with outermost grey being the 95% credible intervals. The red lines are the estimates of F_{MSY} and the dark stippled line is the 20% harvest rate.

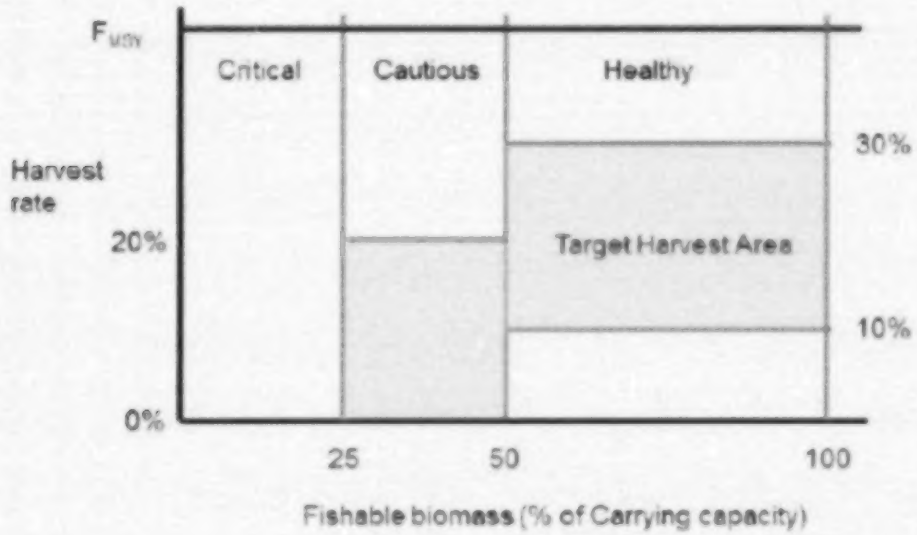


Figure 70: Harvest control rules for the Scotian Shelf snow crab fishery. For the definitions of critical, cautious and healthy zones please refer to the text.

Figure

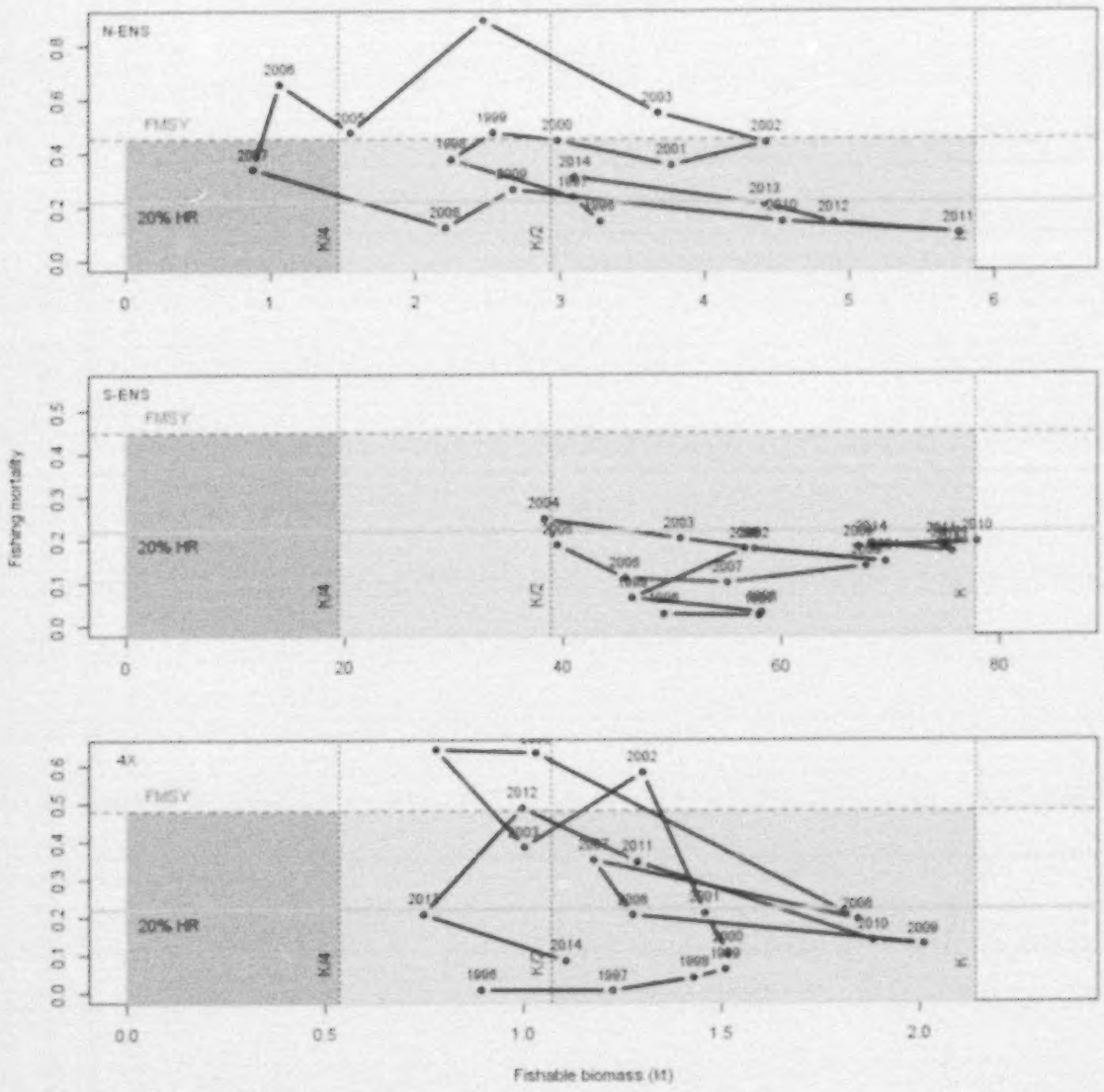


Figure 71: Fishing mortality as a function of fishable biomass for the management areas of the Scotian Shelf snow crab fishery as obtained from the logistic population models. The shaded blocks represent the Harvest Control Rules with red representing the critical zone, yellow the cautious zone and green the healthy zone.

GLOSSARY

Agonistic – Behavioral term relating to aggression, appeasement and avoidance behavior that occurs between members of the same species. Agonistic behavior is a much broader term than "aggression," which simply refers to behavior patterns that serve to intimidate or damage another.

Anthropogenic – Resulting from the influence of human beings on nature.

Benthic – Occurring on the ocean floor.

Biological Reference Points – In the context of the Precautionary Approach, agreed-upon levels of an indicator that are considered bounds to a "healthy" or "unhealthy" population or stock.

Biomass – The abundance of living organisms measured in terms of its weight, mass, volume or caloric energy.

Bitter Crab Disease (BCD) – A fatal disease found in numerous crustacean species worldwide caused by the *Hematodinium dinoflagellate*, a parasite which inhabits the host organism's blood.

Brachyura (Infraorder) – Known as "true crabs" of which the snow crab is a member. Brachyurans are characterized by a body that is short, wide, and flat. The abdomen is reduced from a strong swimming muscle (e.g., shrimp) to a simple flap covering reproductive appendages and carry eggs. The uropods, which along with the telson form the tail fan in other decapods, are totally absent. All five pairs of walking legs are generally large with the first pair being chelipeds. The antennae and antennules are greatly reduced and originate before the eye stalks.

Carapace Condition (CC) – The condition of the shell of a snow crab. Generally related to the age of the organism and the time since last molt. See Table 5 for more details.

> CC1 - Newly molted crab. The top of carapace is light brown and shiny without surface growth of moss or barnacles. Shell is soft and claw is easily broken.
>
> CC2 - The top of carapace is light brown and less shiny with little to no surface growth of moss or barnacles. Shell is clean but hard.
>
> CC3 - The top of carapace is light brown and not shiny. Some growth of moss or barnacles. Shell is hard.
>
> CC4 - The top of carapace is brown and not shiny. Usually some surface growth of moss or barnacles. Shell is hard with small scars. Underneath is yellow brown.
>
> CC5 - Old crab. Carapace is dark brown with substantially mossy ("dirty") surface. Decalcification (black spots) noticeable often at joints. Shell may be soft.

Carapace Width (CW) – The distance across the carapace of a snow crab (millimetres).

Carrying Capacity (K) – The maximum population size of the species that the environment can sustain indefinitely.

Chela – Pincer-like claw of a crustacean or arachnid.

Crab Fishing Area (CFA) – Refers to an individual management area. On the Scotian Shelf they are from north to south: 20 to 24 and 4X.

Commercial Biomass – see Fishable biomass.

Catch per unit effort (CPUE) – The amount caught by a single fishing event, such as the weight or number of crab captured by a single trap haul.

Density – The amount (biomass or number) of crab per unit area.

Distribution (Spatial) – The geographic area in which an organism exists.

Durometer – A calibrated instrument used to measure the hardness of an object (such as a crab shell), scaled from 0 (soft) to 100 (hard). A durometer reading of ≥68 has been historically used to determine a hard shelled crab.

Dynamic – Characterized by continuous change or time. Not fixed.

Ecosystem – The whole of a system with all the interactions between parts, living and non-living.

ENS – Eastern Nova Scotia (essentially Northwest Atlantic Fisheries Organization (NAFO) statistical divisions 4VW).

Exploitation Rate (ER) – The ratio of biomass fished relative to their fishable biomass, where ER(t) = Landings(t) / (Landings(t) + Fishable biomass(t)).

Extrapolate – To infer or estimate by extending or projecting known information.

Fishable biomass (FB) – The biomass of snow crab exploited by the commercial fishery: male, mature, ≥ 95 mm CW and hard shell condition (CC2 to CC5). Note that CC2 snow crab do not have optimal meat yields at the time of the fishery. While immature crab ≥95 mm CW is part of the biomass that can be legally fished, this component is voluntarily returned to allow greater growth.

Fishing mortality (instantaneous) – The exponential rate of death of organisms.

Fishing mortality (relative) –See Exploitation rate.

Generalized Additive Model (GAM). A statistical method used to model and predict values of a variable of interest (e.g., biomass) as a function of non-parametric functions of dependent variables (e.g., temperature, depth, substrate grain-size, etc.).

Harvest Control Rules – A predetermined method for linking biological reference points and exploitation based reference points under the Precautionary Approach to management actions.

Individual Boat Quota (IBQ) –The amount of snow crab allowed to be legally removed by an individual fisher in a given area over a given period of time.

Instar – A stage of an organism between molts (i.e., the hard-shelled phase).

Interpolation – The method of determining unknown values through the use of surrounding known values.

Kriging – A method of interpolation for obtaining statistically unbiased estimates of intrinsic variables (i.e., snow crab biomass density) from a set of neighbouring points with known values, constrained by the relative change in variability of the data as a function of distance.

Larvae – The early, immature form of any animal before the assumption of the mature shape.

Metabolic costs – The amount of energy dispensed by an organism in the process of living (e.g., heat, organic compounds, faeces, urea/uric acid, etc.).

Metabolic gains – The amount of energy gained through the intake of food or other energy sources.

Morphometric maturity – Maturity status determined from measurements of body shape and size. Male snow crab claw height increases very rapidly in the adult stage (terminal molt), whereas females' abdominal width increases with maturity. While morphometric maturity generally coincides with physiological maturity, morphometrically immature males are known to be able to fertilize females.

Molt – The act of growing, through the shedding of an organism's current shell.

Multiparous – Females bearing eggs resulting from their second or third breeding event (mating).

Numerical density – The number of snow crab in a given surface area.

Pelagic – Occurring in the water column (not on bottom).

Pencil-clawed crab – Immature crab that are legally exploitable (≥95 mm CW) but not yet terminally molted. The final growth increment is estimated to increase the body weight by approximately 250%.

Physiological maturity – Biologically (functionally) able to reproduce (even though a crab may not be terminally molted).

Precautionary Approach (PA) – In the context of resource management, management approaches that seeks to not risk the long-term sustainability of a resource, as well as its ecosystem.

Primiparous – Females bearing eggs resulting from their first breeding event (mating).

Recruitment – Snow crab that are expected to enter the fishable biomass in the next fishing season, designates as "R-1".

Sexual dimorphism – When shape and/or size differences exists between sexes of a species.

Soft-shell – Carapace condition in which the shell produces a durometer reading of less than 68 durometer units.

Spatial – Relating to space (such as a given geographic region such as the Scotian Shelf).

Spawning Stock Biomass (SSB) - The biomass of the members of a stock able to contribute to the future propagation of the stock, generally considered as the biomass of mature females.

Substrate – Bottom type on which an animal exists (rocks, boulders, mud, sand, etc.).

Total Allowable Catch (TAC) – the amount of snow crab allowed to be legally removed in a given area over a given period of time.

Temporal – Relating to time (such as a given period of time).

Terminal molt – Snow crab molted for a final time once mature. The size of these crab will not increase further.

APPENDICES

APPENDIX 1: STOCK ASSESSMENT MODEL

A modified discrete logistic model of the fishable biomass component is used to determine the relevant biological reference points (i.e., carrying capacity and F_{MSY}) associated with the harvest control rules of the snow crab fishery. In the fishery literature, this model is commonly referred to as a surplus production or biomass dynamics model. The rationale for using a discrete logistic model is due to its minimal data requirements:

- ageing is currently not possible with Crustacea
- complex life cycle results in high variability of maturity ogives and individual growth trajectories
- a reliable stock-recruitment relationship has not been demonstrated/established

Arguing against the usage of neither the discrete logistic model nor any other standard fishery model is the fact that the fishable component (large males) is not the same as the spawning stock biomass (reproductive females). Due to sex-related differences in longevity, body size/growth, maturity ogives, habitat usage, predation risk and fishery exploitation, any standard model formulation (including the logisitic model) would require a large number of assumptions to convert SSB to the fishable component.

Here, rather than attempting to make any such potentially untenable assumptions, we instead follow the more general formulation of the logistic model as a truncated Taylor series approximation.

For any general variable of state, B (e.g., fishable biomass), its time rate of change is, in general, some function $\mathbf{F}$ of itself and a variety of other parameters θ:

$$dB / dt = \mathbf{F}\ (B;\ \theta)$$

If we proceed with a Taylor series expansion of $\mathbf{F}$ (B=0; θ):

$$\mathbf{F}\ (B;\ \theta) = c_1 B + c_2 B^2 + c_3 B^3 + \ldots ;$$

where c are constants. And only polynomials or order 2 and lower are retained:

$$\mathbf{F}\ (B;\ \theta) \approx c_1 B + c_2 B^2$$

And if we set $c_1 = r$ *and* $c_2 = -\ r/K$ and simplfy, we obtain the basic form of the classical logistic model:

$$\mathbf{F}\ (B;\ \theta) \approx rB\ (1 - B/K)$$

With normalization by K, this simplifies further to:

$$\mathbf{F}\ (B;\ \theta) \approx rb\ (1 - b)$$

Which, in discrete form, becomes:

$$b_t - b_{t-1} \approx r\, b_{t-1}\ (1 - b_{t-1})$$

Removals of the fishable component by a fishery is commonly expressed as an additive term, c, the K-normalized catch:

$$b_t - b_{t-1} \approx r\, b_{t-1}\ (1 - b_{t-1}) - c_{t-1}$$
$$b_t \approx b_{t-1} + r\, b_{t-1}\ (1 - b_{t-1}) - c_{t-1}$$

The intrinsic rate of increase, r, is therefore, some function $\mathbf{G}$ of growth, recruitment, natural mortality, handling mortality and/or incidental bycatch, etc., but excluding fishery catch, c:

$$r = \mathbf{G}\ (growth,\ recruitment,\ mortality)$$

Generally, r and K are assumed constants. These quantities however are not constant, especially given the systemic changes in the SSE associated with the collapse of groundfish in the mid-1990s. We will return to this issue below.

Nonlinear Bayesian state space methods were used to estimate the parameters of this model, θ. This is due to its greater numerical stability; ability to realistically propagate credible errors; ability to estimate unobserved states ("true" fishable biomass); and its ability to simultaneously estimate model "process" errors and data "observation" errors. Process errors (${}_p\sigma^2$) are the uncertainties that feed back into future states via error propagation: for example, via the recursive form of the logistic equation (i.e., errors in b_{t+1} in the state space of b_t *vs* b_{t+1}). Observation errors (${}_o\sigma^2$) refer to the uncertainties associated with measurement and observation (i.e., measurement/data-related errors of both variables in the state space of b_t *vs* b_{t+1}). This latter ability is particularly important as parameter estimates and forecasts based on observation-only errors provide unrealistically optimistic (small and constant) error bounds; and parameter estimates and forecasts based on process-only errors expand rapidly into the future, resulting in potentially unrealistically pessimistic (large and usually growing) error bounds.

The main distributional assumptions of the model of fishable biomass are as follows. The reader is referred to the code below for the distributional assumptions and derivations of each of the specific priors.

As the fishable biomass of snow crab follows a lognormal distribution, a multiplicative observation error model was assumed, with a variance $\sigma^2_{t,o}$. The observed fishable biomass index O_t was assumed to be linearly related to the "true" unobserved fishable biomass by a proportionality constant q such that $O_t = q\ K\ b_t$ for each of the three separate CFAs, denoted by a:

$$O_{t,a} \sim Lognormal\ (\ log(q_a\ K_a\ b_{t,a}),\ {}_o\sigma^2{}_a\ )$$

The "~" indicates "is distributed as", which in this case is a lognormal distribution with mean $log(q_a\ K_a\ b_{t,a})$ and variance ${}_o\sigma^2{}_a$. The prior on the observation error, ${}_o\sigma^2{}_a$, was set to be lognormal with mean and standard deviation of -2.559 and 0.69.

Catchability, q, is a factor that simplistically quantifies the influence of a number of differing biases, including survey gear, survey protocols, areal expansion protocols, survey stratification and statistical modeling, etc. It is overly simplistic as such biases are non-constant over time and space. However, here, it serves as a first-order estimate of such influences. Historically, it was assumed to be 1 due to the nature of the sampling design and analytical methodology. For modeling purposes, it is separated into two components for each of spring (pre-2004) and summer (post-2004) surveys:

$$q_a \sim dunif\ (0.1,\ 4)$$

Process error was assumed to follow a (multiplicative) lognormal distribution with variance ${}_p\sigma^2$ whose prior was log-normally distributed with mean and standard deviation of -2.559 and 0.69. Normalized catch, c, assumed to be known without error:

$$b_{t,a} \sim Lognormal\ (\ log(b_{t-1,a} + r_{t-1,a}\ b_{t-1,a}\ (1 - b_{t-1,a}) - c_{t-1,a}),\ {}_p\sigma^2{}_a\ )$$

Carrying capacity was assumed to follow a log-normal distribution:

$$K_a \sim Lognormal\ ({}_K\mu_a,\ {}_K\sigma^2{}_a\ )$$

Where the area specific ${}_K\mu_a$ and ${}_K\sigma^2{}_a$ were chosen based on previous knowledge of the production in the area and were set to ln(1.83,0.22), ln(4.17,0.2) and ln(0.78,0.16) for N-ENS, S-

ENS and 4X, respectively. The intrinsic rate of increase was assumed to be stationary with a prior of

$$r_a \sim Normal\ (0.96, 0.4)$$

These priors were marginally informative. For carrying capacity, the distribution was assumed to be bounded to be within previously estimated historical maxima. For the intrinsic rate of increase, the distribution was chosen to center on ~1. This is loosely based upon estimates of $\mu \approx 1$ for crab of similar longevity and body size, *Cancer pagurus* in Europe (Laurans and Smith 2007). The posterior distribution of the parameters of interest, θ, conditional upon the data were estimated via MCMC (Gibbs) sampling using the JAGS platform (Plummer 2003, 2010). Three Markov chains were followed to ensure convergence; 4,000 simulations in the burn-in phase were sufficient to ensure such convergence of the Markov chains. Another 2,500,000 simulations were used to describe the posterior distributions of the parameters. A thinning of 500 simulations was required to minimize autocorrelation in the sampling chains.

Other models were also examined based upon the penalized Deviance Information Criterion (Plummer 2008); however, their performance was generally similar.

The JAGS model used for parameter estimation is as follows:

```
model {
 #priors for r,K,q
for (j in 1:U) {    r[j] ~ dlnorm( r.mu[j], pow( r.sd[j], -1 ) )   }
for (j in 1:U) {    q[j] ~ dunif( q.min[j] , q.max[j] )  }
for (j in 1:U) {    K[j] ~ dlnorm( K.mu[j], pow( K.sd[j], -1 )) # T(K.min[j], K.max[j] )  }
 # ------------
 # removals (catch) observation model, standardized to K (assuming no errors in observation of catch!)
  for (j in 1:U) {   for (i in 1:N){   rem[i,j] <- CAT[i,j]/K[j]     }  }
 # biomass observation model
 #   This is slightly complicated because a fall / spring survey correction is required:
 #   B represents the total fishable biomass available in fishing year y
 #     in fall surveys:    Btot(t) = Bsurveyed(t) + removals(t)
 #     in spring surveys:  Btot(t) = Bsurveyed(t) + removals(t-1)
  for (j in 1:(U)) {
   bo.sd[j] ~ dlnorm(bo.mup[j],pow(bo.sdp[j],-1))
   bo.tau[j] <- pow( bo.sd[j], -2 )   }
  for (j in 1:(U-1)) {
   # spring surveys from 1998 to 2003
   IOA[1,j] ~ dlnorm( log( max( q[j] * K[j] * (bm[1,j] - rem[1,j]) , eps)), bo.tau[j] ) # approximation
   for (i in 2:(ty-1)) {
    IOA[i,j] ~ dlnorm( log( max( q[j] * K[j] * (bm[i,j]- rem[(i-1),j]), eps)), bo.tau[j] )    }
   # transition year
   IOA[ty,j] ~ dlnorm( log( max( q[j] * K[j] * (bm[ty,j] - (rem[(ty-1),j] + rem[ty,j] )/2 ), eps)), bo.tau[j] ) ; # approximation
   # fall surveys
   for (i in (ty+1):N) {
    IOA[i,j] ~ dlnorm( log( max( q[j] * K[j] * (bm[i,j] - rem[i,j]), eps)), bo.tau[j] ) ;  } }
  # Cfa 4X -- fall/winter fishery
  # assume similar to a spring fishery but no need for separate q's
  #   Btot(t) = Bsurveyed(t)+ removals(t-1)
                #   NOTE: year designation in 4X is for the terminal year: ie. 2001-2002 => 2002
  IOA[1,cfa4x] ~ dlnorm( log( max( q[cfa4x] * K[cfa4x] * (bm[1,cfa4x] - rem[1,cfa4x]), eps)), bo.tau[cfa4x] ) ; #
approximation
  for (i in 2:N) {
   IOA[i,cfa4x] ~ dlnorm( log( max( q[cfa4x] * K[cfa4x] * (bm[i,cfa4x]- rem[(i-1),cfa4x]), eps)), bo.tau[cfa4x] ) :   }
 # ------------
 # biomass process model
        for (j in 1:U) {
    bp.sd[j] ~ dlnorm(bp.mup[j],pow(bp.sdp[j],-1))
   bp.tau[j] <- pow( bp.sd[j], -2 )   }
  for(j in 1:U) {
   b0[j] ~ dunif( b0.min[j], b0.max[j] ) # starting b prior to first catch event
   bm[1,j] ~ dlnorm( log( max( b0[j], eps)), bp.tau[j] ) T(b.min, b.max) ; # biomass at first year
   for(i in 2:(N+M)) {
    bm[i,j] ~ dlnorm( log( max(bm[i-1,j]*( 1 + r[j]*(1-bm[i-1,j])) - rem[i-1,j] , eps)), bp.tau[j] ) T(b.min, b.max) ;    }
 # forecasts
   for(i in 1:M) {
    rem[N+i,j] <- er*bm[N+i-1,j]    } }
 # ------------
 # monitoring nodes and parameter estimates for output
  for(j in 1:U) {
   MSY[j]   <- r[j]* exp(K[j]) / 4  # maximum height of of the latent productivity (yield)
   BMSY[j]  <- exp(K[j])/2  # biomass at MSY
   FMSY[j]  <- 2 * MSY[j] / exp(K[j]) }# fishing mortality at MSY
# ------------
  # fishing mortality
  # force first year estimate assuming catches in year 0 to be similar to year 1
  for(j in 1:U) {
   for(i in 1:N) {
    F[i,j] <- -log( max(1 - rem[i,j] / bm[i,j], eps))   }
   for(i in (N+1):(N+M)) {
    F[i,j] <- -log( max(1 - er * bm[i-1,j] / bm[i,j], eps))  } }
  # ------------
```

APPENDIX 2: CONTEXT OF THE PRECAUTIONARY APPROACH

In the context of natural resource management, the precautionary approach (PA) identifies the importance of care in decision making by taking into account uncertainties and avoiding risky decisions. This is because natural ecosystems are intrinsically complex and unexpected things can and often do happen (e.g., Choi and Patten 2001). The origin of the PA is diffuse but has its first precursor in Rachel Carson's 1962 book, Silent Spring, which caused widespread concern about the use of synthetic pesticides and eventually resulted in the abolition of DDT in many parts of the affluent world. The Stockholm Declaration of the United Nations Conference on the Human Environment (UNCHE 1972) was the first international environmental law recognizing the right to a healthy environment. This was taken a little further by the World Commission on Environment and Development (WCED 1987, or the Brundtland Commission's Report "Our Common Future"), which highlighted the need for sustainable development. Subsequently, another conference was undertaken in Rio de Janeiro, Brazil (1992), which attempted to establish international agreements to protect the integrity of the environment while recognizing state sovereignty and, therefore, state responsibility for providing equitable resources for both present and future generations. Sustainable development, public participation in the decision making process (especially youth, indigenous people and women), environmental impact assessments and management in particular of environmental pollution and degradation, especially when harmful to human health, were key points of agreement.

Many other international agreements were undertaken that re-affirmed these positions: the UN Convention on the Law of the Sea (UNCLOS 1982) that recognized territorial jurisdiction with a pollution focus in the Exclusive Economic Zone; the FAO (1995) Code of Conduct for Responsible Fisheries emphasizing conservation and the PA, promoting selective fishing gear and responsible fishing methods; the UN Fishing Agreement (UNFA 2001) dealing with straddling and highly migratory fish stocks; the UN Convention on Biological Diversity which identified Ecosystem-Based Management as a global responsibility; the World Summit on Sustainable Development (WSSD 2002) in Johannesburg reaffirmed the common agreement to "maintain or restore stocks to levels that can produce the maximum sustainable yield with the aim of achieving these goals for depleted stocks on an urgent basis and where possible not later than 2015".

Canada, as a signatory to these international agreements, has a legally binding obligation to manage natural resources using a PA (DFO 2005, 2006; Shelton and Sinclair 2008). Ultimately, a PA means to not risk the long-term sustainability of the resource in focus and the ecosystem in which it is embedded. Fortunately, fostering the long-term sustainability of a natural resource in a fishery context also has the direct consequence of fostering the highest possible catch rates (CPUE) and associated socio-economic benefits of an efficient and vigorous fishery. Fostering the long-term biological and ecological sustainability can, therefore, foster the long-term socio-economic sustainability of the dependent industry.

Sustainability

Implementing a PA to resource management requires the careful consideration of all sources of information relating to the sustainability of both the resource in focus and the ecosystem in which it is embedded: scientific and traditional information and associated uncertainties. A further requirement is a transparent mechanism for synthesizing this information and measuring the sustainability of the resource. The latter is required in order to provide feedback upon the success or lack thereof of specific management actions. To address this requirement, DFO (2006) suggested the use of spawning stock biomass (SSB) as a measure of "sustainability". High levels of SSB were to be considered "healthy" and low levels "unhealthy". Similarly, in the snow crab fishery, the focus is naturally upon the exploitable component: the "fishable biomass".

If the relative abundance of fishable biomass is high, most fishers, fisheries managers and fisheries scientists would consider it to be in a more "sustainable" state, and vice versa.

Unfortunately, this perspective is problematic. High abundance can cause a destabilization and collapse of a population through over-crowding, habitat degradation, disease and other density-dependent mechanisms. Well known examples include deer on islands that eventually overpopulate and eat themselves to extinction; humans on Easter Island that have over-harvested trees leading to population, societal and ecological collapses; or, the over-dominance of species (monocultures in farms and forests) that results in disease or fire outbreaks and eventually large-scale collapse (Diamond 2005). A high abundance does not necessarily equate to high sustainability. The problem lies with not the metric, but rather the focus upon a single indicator. Sustainability is a multidimensional concept that requires reliance upon a broader set of criteria that describes both the resource status and relationships between the focal resource and the surrounding ecosystem (Choi and Patten 2001).

For example, a sustainable snow crab population requires, *at a minimum*: stable and positive levels of egg production, recruitment and stable and comparable levels of natural mortality and ecosystem structure and function. "Natural mortality" and its converse, "recruitment" are of course catch-all terms that are actually quite complex, involving age and size structure, sex ratios, genetic diversity and numerous ecosystem-level interactions (e.g., habitat variability, resource availability, predation, contaminant loads, disease prevalence, nutrient regeneration and mixing, carbon flux, control of invasive species). Any rapid change in one or more of these potential determinants of sustainability can undermine the long-term sustainability of snow crab. As all of these factors are variable in time and space, the stock assessment of snow crab in the ESS is highly attentive of these potential determinants of population and ecosystem sustainability.

The primary tools of fishery management are the control of fishing catch and effort. Generally, by reducing catch and effort, stock status and/or ecosystem context is expected to improve. However, the lack of recovery of cod since the cod-moratorium in the early 1990s in Atlantic Canada, suggests that even this "universal" expectation of fisheries control is more a belief than reality. A more risk-averse management approach would, therefore, seem to be prudent. For the snow crab fishery, the need for additional precaution is further demanded by the fact that the Scotian Shelf is the southern-most limit of the spatial distribution of snow crab. If environmental fluctuations occur in oceanographic currents and bottom temperatures, this is the area that can be expected to be most significantly influenced by such changes.

Ultimately, a population that is "sustainable" is one that is able to maintain the tenuous balance between the various conflicting demands placed upon it by the ecosystem in which it resides, in addition to the humans that influence or exploit it. The maintenance of this balance operates on many space-time scales and, therefore, requires adaptability (long-term – evolutionary processes) and resilience (short-term – ecological and population dynamic processes). To increase the chances that fishing practices and management actions will result in a sustainable resource, the fisheries influence must simply be small enough that the ability of a population to maintain this balance (adaptability and resilience) is not overtly disturbed or damaged. This requires that the footprint of the fishery (i.e., magnitude of its influence upon this ability) be small, relative to the biological footprint of the population (i.e., magnitudes of egg production, recruitment, "natural" mortality, and numerous other ecosystem-level processes).

Significantly, as the footprint of a fishery is itself context dependent (i.e., population and ecosystem), the use of fixed biological limit reference points of a single indicator is not at all PA-compliant as they are not sensitive to natural and human-induced alterations in the ecosystem context. To determine appropriate thresholds and reactive/mitigative measures for each

ecosystem trait is also untenable due to the sheer size and complexity of the SSE and the longevity of the snow crab. However, relevant indicators are evaluated to at least detect rapid alterations. This information is used qualitatively and quantitatively to provide the context by which the snow crab fishery footprint is assessed. The magnitude of the fishery footprint is minimized aggressively when greater uncertainty is associated with this context (environmental variability, age and size structure irregularities, etc.). For example, if recruitment is poor or environmental conditions erratic, then a more conservative approach (lower exploitation rate) is adopted. Further, all scientific information is brought forward and deliberated in an open and transparent manner with scientists, managers, fishers, aboriginal groups and various stakeholders, as per the Rio Accord (UNCED 1992).

Reference Points

Many pre-existing existing management measures and fishing practices in the snow crab fishery of area 4VWX are precautionary:

- Reproductive potential of the spawning stock biomass is not disrupted as only mature males are exploited. The fishery does not remove females.
- Mature males are exploited mostly after the mating season (spring), reducing the possibility of sperm-limitation and potential genetic selection towards earlier (i.e., smaller) size at maturity.
- Conservative exploitation strategies have generally been the norm, especially in recent years. Harvest rates are amongst the lowest in the Northwest Atlantic, usually ranging from 10% to 30% of the fishable biomass. This precaution is warranted as this stock is at the southern-most limit of the spatial distribution of snow crab in the western Atlantic. If fluctuations occur in environmental factors, such as oceanographic currents and/or bottom temperatures, this area could be significantly influenced. Further, the persistent collapse of groundfish in the area suggests that species in this area may be susceptible to collapse and subsequent existence in a collapsed state.
- Refugia from directed fishing pressures exist in the Gully MPA, along the continental slope, and much of the western inshore portion of CFA 24. Movement within all subareas has been observed, with mean distance traveled being 10-20 km/annum, with high variability (>200 km/annum maximum).
- Sub-legal (<95 mm CW) mature males and immature males are able to mate. As a result, even if the abundance of commercially exploitable mature males were severely depleted, this would not be a conservation issue. This is especially the case as female crab are not exploited.
- Immature and soft-shelled (newly-molted, easily damaged) crab are not harvested and handling mortality is minimized via area closures and at-sea-observer monitoring of soft-shell incidence helping to maximize the potential yield per animal to the biomass.
- Traditional and fishers' knowledge is incorporated by DFO Science into assessment approaches; fostering self-knowledge and long-term sustainability perspectives/stewardship by industry. This is achieved through open and transparent consultations and communications between all stakeholders' (fishers, aboriginal groups, NGOs, managers and scientists).
- This fishery is well monitored through 100% dockside monitoring, at-sea-observer coverage (5-10% of landings) and mandatory VMS (Vessel Monitoring System) usage in most areas.

To reiterate, the primary objective of the above management measures and practices attempt to balance the stability processes operating on long-term (adaptability) and short-term (resilience) (see Choi and Patten 2001) in order to maintain the sustainability of the snow crab population as a whole and the fishery that is dependent upon it. It is, therefore, explicitly PA-compliant.

Even with these measures, knowledge of biological reference points for the targeted fraction of the population (mature males >95 mm CW) are required to guide annual TAC advice and related management measures. There is no 'correct' or 'best' choice of reference points, especially given the fact that the underlying carrying capacity is variable over time; recruitment has been episodic and the SSB remains protected. In other words, the 4VWX snow crab population is not at, nor near any equilibrium state. As a result, the parameter estimates from the logistic model provide only first order estimates of the true biological reference points (see Methods).

APPENDIX 3: ECOSYSTEM INDICATORS

The variables used as indicators in this study are listed and described in the following:

Index variable label	Description
NS: population size	Total population size for Nova Scotia, a proxy of the influence of human on the Scotian Shelf
CIL volume	Cold intermediate layer (water temperature < 3°C) in the Gulf of St. Lawrence from the September groundfish hydrographic survey.
CPR: Calanus finmarchicus 1-4	Continuous Plankton Recorder (CPR) relative abundance estimates: *Calanus finmarchicus* instars 1 to 4
CPR: Calanus finmarchicus 5-6	Continuous Plankton Recorder (CPR) relative abundance estimates: *Calanus finmarchicus* instars 5 to 6
CPR: colour	Continuous Plankton Recorder (CPR) relative estimate surface ocean color, a proxy for Chl-a concentrations
CPR: diatoms	Continuous Plankton Recorder (CPR) relative abundance estimates: Diatoms
CPR: dinoflagellates	Continuous Plankton Recorder (CPR) relative abundance estimates: Dinoflagellates
Employment per total landed value	Number of fishers employed per total landed value of the fishery
Employment per total landings	Number of fishers employed per total landings of fish
GDP: fish processing	Gross Domestic Product: fish processing sector in Nova Scotia
GDP: fishing and hunting	Gross Domestic Product: fishing and hunting sector in Nova Scotia
GDP: NS total	Gross Domestic Product:Total for Nova Scotia
GDP: oil and gas	Gross Domestic Product: Oil and gas sector in Nova Scotia
Gulf stream front: lat@-62 lon	Gulf stream front location at -62 longitude (latitude)
Ice coverage	Sea ice coverage, cumulative seasonal sum
Landed value: all	Landed value of all fish and invertebrates
Landed value: groundfish	Landed value of all groundfish in Nova Scotia
Landed value: pelagics	Landed value of all pelagic fish in Nova Scotia
Landed value: shellfish	Landed value of all shellfish
Landings: all	Total landings of all fish and invertebrates
Landings: groundfish	Total landings of all groundfish
Landings: pelagic	Total landings of all pelagic fish
Landings: shellfish	Total landings of all shellfish
NAO index	North Atlantic Oscillation index anomaly of December-February sea level atmospheric pressure difference (kPa) between the Azores and Iceland. This index has been shown to be related to air temperatures, SST, convection and circulation changes in the North Atlantic and through atmospheric tele-connections, even broader-scale forcings.
No. fish harvesters	Number of fish harvesters in Nova Scotia
No. shellfish closures	Number of shellfish closures
No. wells drilled	Number of oil and gas wells drilled on the Scotian Shelf
NS: % 65 and older	Nova Scotia demographics
NS: % attending university	Nova Scotia demographics
PCBs: puffins	PCB concentrations in Atlantic puffins
PCBs: seals	PCB concentrations in grey seals
RV: biomass capelin	Research survey estimates of capelin biomass
RV: biomass cod	Research survey estimates of cod
RV: biomass elasmobranchs	Research survey estimates of elasmobranch fish
RV: biomass flatfish	Research survey estimates flatfish
RV: biomass gadoids	Research survey estimates gadoids
RV: biomass large demersals	Research survey estimates large demersal fish
RV: biomass large pelagics	Research survey estimates large pelagic fish
RV: biomass small demersals	Research survey estimates of small demersal fish
RV: biomass small pelagics	Research survey estimates small pelagic fish

Index variable label	Description
RV: bottom oxygen	Research survey estimates of bottom oxygen concentration
RV: bottom salinity	Research survey estimates bottom salinity
RV: bottom temperature	Research survey estimates bottom temperature
RV: condition elasmobranchs	Research survey estimates of elasmobranch physiological condition
RV: condition flatfish	Research survey estimates of flatfish physiological condition
RV: condition gadoids	Research survey estimates of gadoid physiological condition
RV: condition large demersals	Research survey estimates of large demersal physiological condition
RV: condition large pelagics	Research survey estimates of large pelagic physiological condition
RV: condition small demersals	Research survey estimates of small demersal physiological condition
RV: condition small pelagics	Research survey estimates of small pelagics physiological condition
RV: groundfish SMR	Research survey estimates of mass specific metabolic rates of all fish
RV: no. taxa predicted at 100 km^2	Research survey estimates of the number of taxa predicted at 100 km^2
RV: Shannon index	Research survey estimates of the Shannon diversity index of fish species
RV: species-area exponent	Research survey estimates the mean species-area exponent on the Scotian Shelf. The average scaling exponent derived from a species richness vs surface area relationship for the fish community, using a spatially constrained (locally calculated saturation curves within a radius of 10 to 300 km) fractal-like approximation method.
RV: species-area intercept	Research survey estimates the mean species-area intercept on the Scotian Shelf. The average scaling exponent derived from a species richness vs surface area relationship for the fish community, using a spatially constrained (locally calculated saturation curves within a radius of 10 to 300 km) fractal-like approximation method.
RV: taxonomic richness (100 km)	Research survey estimates the mean number of taxa observed at 100 km^2 scale
Seal abundance adult	Abundance of seal adults
Seismic 2D; km	The length of seismic exploration tracks; km
Seismic 3D; km^2	The amount of seismic exploration conducted (3D); km^2
Shelf front: lat@-62 lon	Shelf front location at -62 longitude (latitude)
Shrimp: abundance index	Shrimp abundance index from shrimp surveys
Shrimp: capelin abundance index	Capelin abundance index for areas overlapping the shrimp fishery
Snow crab: habitat area	Snow crab survey estimates of snow crab potential habitat area (km^2) determined from temperature and depth masks
Snow crab: immature female abundance	Snow crab survey estimates of immature female abundance (no.)
Snow crab: landings	Snow crab total landings
Snow crab: male recruitment	Snow crab survey estimates of male recruitment
Snow crab: mature female abundance	Snow crab survey estimates of mature female abundance (no.)
Snow crab: mature female mean size	Snow crab survey estimates of female mean size
Snow crab: mature male biomass	Snow crab survey estimates of male mean biomass (kt)
Snow crab: mature male mean size	Snow crab survey estimates of mature male mean size
Snow crab: temperature mean	Snow crab survey estimates of mean temperature in the snow crab potential habitat
Snow crab: temperature SD	Snow crab survey estimates of the standard deviation of the mean temperature in the snow crab potential habitat
Temperature: Sable Is.	Temperature at Sable Island
Temperature: SST Halifax	Temperature: sea surface temperature at Halifax station